Semiconductors for RRH 2019

Abstract: A complete technical and market review of ASIC, FPGA, RFSoC, ADC, DAC, LDMOS, GaN, PLL, and RF components in remote radio heads. The RRH block diagram is shown in multiple ways to illustrate trends in component integration, transceiver architecture, and component pricing. The forecast includes pricing, shipment, revenue, and market share data for each component type through 2024.

MOBILE EXPERTS

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Semiconductors for RRH 2019

FIGURES

CHARTS

Semiconductors for RRH 2019

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1 EXECUTIVE SUMMARY

This year, the semiconductors in the macro base station market are going through a transformation. The traditional separation between digital processing and data converters has been bridged, and now the RFSoC is quickly taking over the block diagram… leaving the data converter suppliers with a smaller opportunity and moving one step closer to complete integration of the radio.

Massive MIMO is the main driver of the change. With each RF path transmitting lower power, the level of performance required for each path is a bit lower. In addition, the latest process nodes make it possible to integrate ADC/DAC with the processor, taking advantage of the high performance of 16-to-20 nm geometries in the gates.

Of course, the sheer numbers of massive MIMO transceivers drives a boost in the RF semiconductor market. The opportunity for RFSoCs and power transistors will double from 2018 to 2020. The 5G market will be lumpy due to uneven global deployment, but the step up to Massive MIMO will leave our baseline market at a higher level overall.

It's not good news across the board, as some PLLs and small-signal devices will be integrated out of the block diagram. Discrete data converters will still be around, but the growth opportunity is not there for the basic discrete devices anymore.

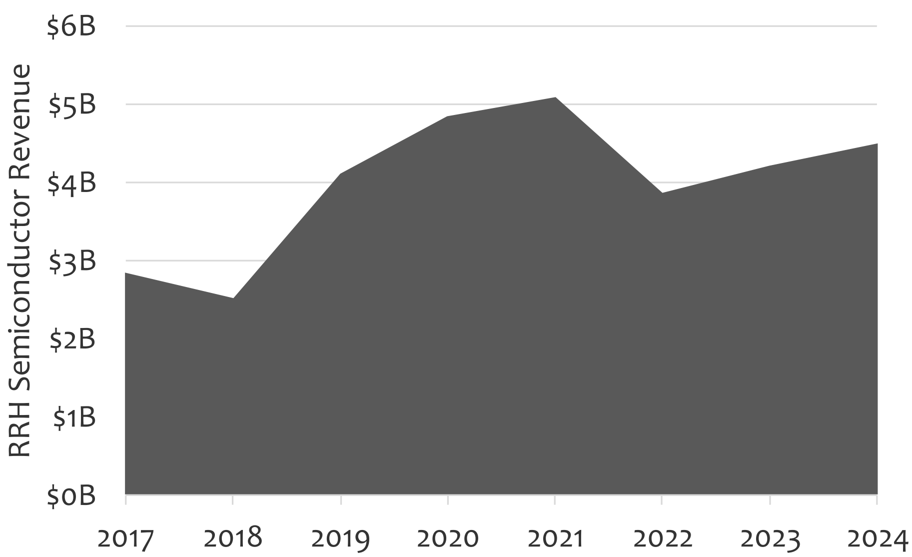

Chart 1: Semiconductor Market Size in RRH Applications, by component type, 2017-2024

Source: Mobile Experts. NOTE: Includes 2G, 3G, 4G, and 5G macro RRH (over 40W composite power and below 6 GHz).

2 MARKET BACKGROUND

Finally, 5G has arrived and we can now see the impact of a new wave of investment. In China, the 5G ramp has already driven major investment in RF semiconductors, and multiple technical changes that are reshaping the market:

- Frequencies are moving up. 5G deployment is happening at 2.6 GHz, 3.5 GHz, and 4.8 GHz.
- Bandwidth is wider, with many 5G deployments at 100 MHz bandwidth (below 6 GHz).
- Massive MIMO changes the architecture so that the number of physical transceivers is leaping to much higher levels. This drives higher integration for processors and mixed-signal devices as well as lower power for RF amplifiers.
- Beamforming adds a new load to the processors, along with a wholly new dimension of system level optimization which will require flexibility in the processor for years.

At a business level, the demand for 5G is more clear this year, and we are able to verify that operators are enthusiastic about investing. A major deployment was rolled out very quickly in Korea, and a gigantic deployment in China has started its early stages. We're starting to see that nationwide deployments at 3.5 GHz will be more common than we assumed in the past.

Political dynamics and national policy will come into play here. The Chinese government is determined to deploy nationwide 5G with three major operators, driving a sudden ramp during 2019. The vendor response to this surge of deployment will cause havoc in the lower tiers of the supply chain….for example, Huawei spent the first five months of 2019 stocking up on inventory, then was cut off from American semiconductors. As a result, Huawei is producing 5G base stations today despite its inability to buy parts. This unusual situation leaves a high degree of uncertainty in the market. If the USA/Huawei situation is resolved quickly, then we have an inventory bubble to contend with and suppliers will suffer for a few months. If the situation is not resolved, then Huawei stands to lose its share of the 5G market and will scramble to push Chinese domestic alternatives into production.

Market Drivers

Make no mistake, the driver for the mobile infrastructure market is pure and simple: when people use more mobile data, they need more RRH units. The change to 5G can be confusing with talk about Virtual Reality and self-driving cars, but in fact these apps don't have any impact on the base station numbers so far. Deployment of 5G is happening to beef up the capacity of LTE networks—which are reaching their limits.

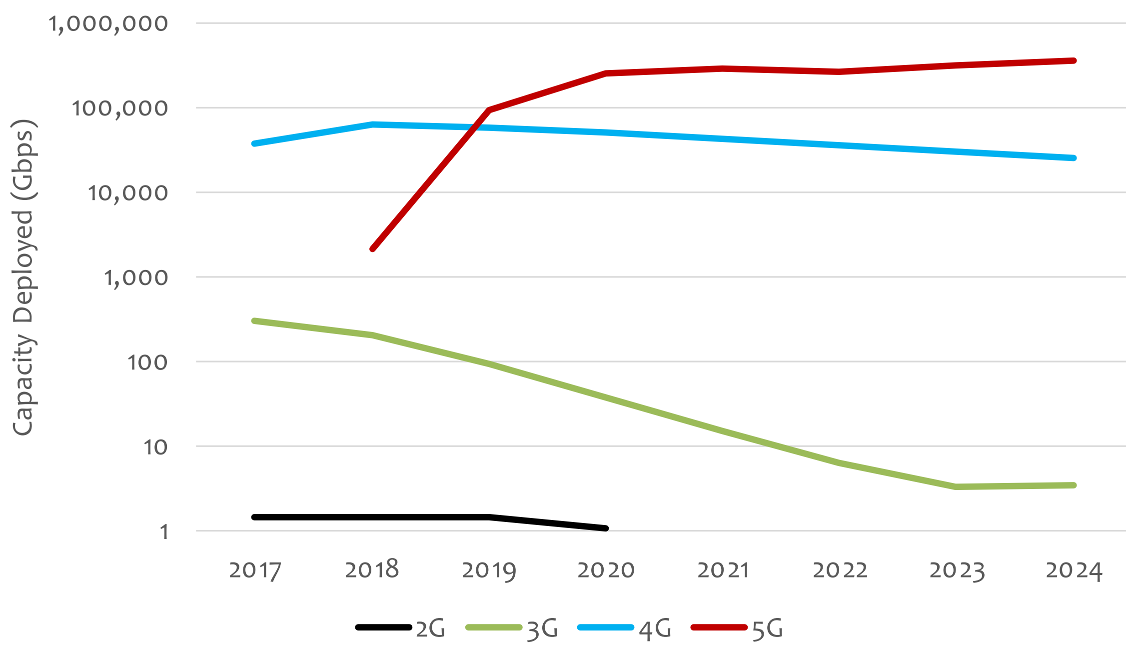

Chart 2: Capacity Deployment for 2G, 3G, 4G, 5G infrastructure,, 2017-2024

Source: Mobile Experts

Because 5G is about 15% better than 4G in terms of the waveform's natural spectral efficiency, and it's more flexible for future applications, almost every mobile operator with a new band will use 5G NR as the standard. This change in itself would not change the RRH architecture very much, as the level of processing and RF functions would be almost the same.

The new frequency bands to be deployed (notably in the 2.6 , 3.5, and 4.8 GHz bands) have a wider bandwidth than previous bands below 2.4 GHz. In general, each operator will have 100 MHz to work with, so this requires wider performance from the radio chain.

The biggest change comes from the addition of Massive MIMO. Changing from 2-4 transceivers to 64 transceivers per RRH is a major leap for the RF architecture. Instead of a few heavy-duty LDMOS amplifiers, OEMs are now using 64 smaller plastic-packaged GaN or LDMOS amplifiers. The JESD204 lanes for interface between processors and data converters become a power/heat nightmare for Massive MIMO, so everyone has chosen to integrate these interfaces out of the design, with RF Systems on Chip (RFSoCs). And the antenna is now integrated with the RRH with beamforming control.

Overall, 2019 will be remembered as the year that the radio architecture changed dramatically, with a rapid ramp to major 5G deployment.

WHERE MASSIVE MIMO DOESN'T MAKE SENSE

Massive MIMO has the effect of boosting spectral efficiency…as we stated before, in general the number goes from 2 bps/Hz to 6 bps/Hz, with wide variation based on the situation. Of course, boosting spectral efficiency results in more capacity.

Using Massive MIMO to add capacity comes at a cost. The primary cost is related to the large size of the antenna array that's involved. At 3.5 GHz, a 32T array is reasonable, but Korean operators have chosen not to use 64T arrays due to the space available on rooftop and tower sites.

Below 1 GHz, the longer wavelength of the RF signal means that the cost is higher to use a large array. A 64T array at 700 MHz would be, like an old joke, the size of a barn door. Mounting such a large antenna would cost thousands of dollars per month on a leased tower, and would require serious structural support to avoid twisting/bending problems in a heavy wind.

At the same time, the benefit from Massive MIMO in a sub-1 GHz FDD band would be minimal. The channel bandwidths in those bands range from 10 to 15 MHz, so the boost in capacity with Massive MIMO would be about 40 Mbps. We believe that the heavy costs of large antennas outweigh the benefit of another 40 Mbps of capacity.

For this reason, Mobile Experts forecasts Massive MIMO upgrades only for wider bands, where 20 MHz or more spectrum can be upgraded…and our expectations for Massive MIMO are much higher for the 2 GHz bands than for 1 GHz bands.

COMBINING BANDS TO REDUCE RRH COUNT

For many years, operators have talked about buying dual-band radios in order to reduce the number of radio units on the tower. The driving force behind this is the cost of renting or owning space on towers….with 5 LTE bands, simply mounting five separate RRH units on steel brackets can be problematic.

Tower leasing companies such as Crown Castle and American Tower can charge as much as $1,000 per month for each RRH unit (not counting the cost of the antenna). So, assuming a shared antenna, every new band adds considerable operating expense. The lease cost is so high that the CAPEX cost of buying the RRH itself is really not that meaningful!

As a result, there is pressure on suppliers to come up with more efficient ways to combine radios into shared enclosures. There are two ways to do this: Either two separate radios share a single box, or a wideband radio can be used to cover two bands.

Despite 15 years of requests by the operators, the number of dual-band radios sold has been limited. The concept of "two radios in one box" has worked to some degree, but the sheer number of combinations for different bands and requirements has led the OEMs to only offer this solution to a few of the larger operators. It's simply not worthwhile for OEMs to develop a special product for a smaller mobile operator. In the other case, wideband radios have not been widely used because the efficiency of wideband amplifiers has been poor, leading to excessive heat in a single box.

This pressure remains in the market, and the market background conditions are not changing (at least for the FDD bands)…so there's still an opportunity for vendors that can create modular designs or wideband designs with good performance.

Today, 4x4 MIMO is available on premium smartphones, at least for bands above 1.8 GHz. Also, Multi-User MIMO (MU-MIMO) is available as an option in the base station software for some systems, making higher antenna count useful in the network. Note that we don't expect to see any phones with 4x4 MIMO below 1 GHz due to the long wavelengths in these low bands, which cause antenna limitations.

The Inventory Bubble

It's clear that Huawei has been stockpiling inventory of power transistors, FPGAs, and other devices. Somehow, Huawei knew that the US government would be cutting off their access to US semiconductors, and they were able to purchase roughly 20 million extra power amplifiers and at least one million extra RFSoCs before their shipments were stopped.

We have accounted for this inventory bubble in our forecast, by adding 20 million extra massive MIMO transceivers to our 2019 forecast and then subtracting 20 million from our 2021 forecast. The timing for the bubble to burst is purely speculative…nobody knows when the political issue will be resolved, and when Huawei will return to a normal inventory flow.

3 TECHNOLOGY FACTORS

Shifting to 5G and Massive MIMO leads to a major disruption in the RRH block diagram. The industry had become pretty stable, with every OEM using similar ASICs, FPGAs, Doherty devices, DPD, and ADCs/DACs from two major vendors. It was in danger of boring analysts to death.

Then, Massive MIMO came onto the scene and now the RRH is going through a major disruption in technology. The old rules about ASICs and FPGAs have changed. The combination of DPD and Doherty for big, beefy PAs has shifted to lighter predistortion and smaller PAs. And integration is removing some of the discrete blocks from the RRH altogether.

The major limiting factors for RRH design remain the same as always:

1. Heat dissipation is a limitation for new RRH units. Massive MIMO radios, dual-band radios, and compact designs will all drive dense heat dissipation in the RRH. The companies that can address this issue best will win.
2. Size is an issue as well. As active antennas are deployed, they'll be integrated with passive antennas. So far we have not seen sufficient progress along these lines, as the passive/active antenna combinations are HUGE.

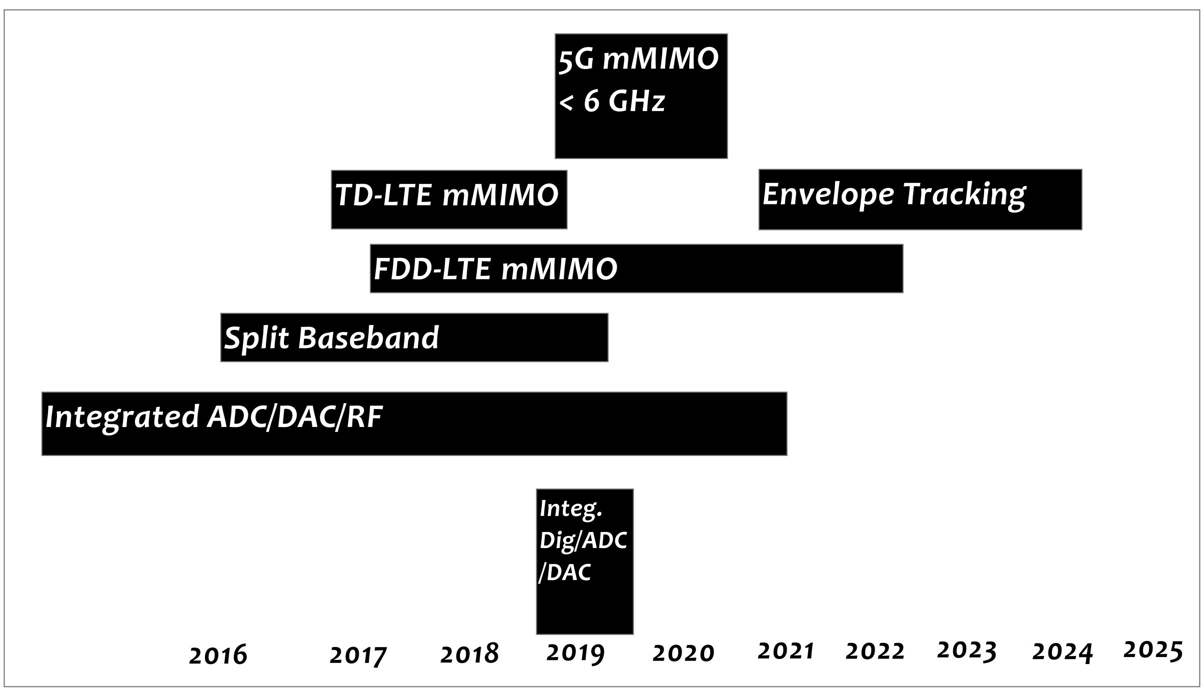

Figure 1 Timeline for New Technology Introduction

Source: Mobile Experts

Boxes reflect the time span between the date of first deployment in the field, and the date when 10% of sites use each technology in a major network.

Note that Cloud RAN, CoMP, and eICIC are not considered within the scope of this report, because these features do not directly impact the RF semiconductors in a Remote Radio Head.

IMPACT OF THE 5G WAVEFORM

The 5G NR waveform and other features such as Massive MIMO are not the same thing. The 3GPP work defines a new frame structure for LTE which offers flexibility for high reliability packets, as well as lower round-trip latency in the radio path. The improvement in data capacity per MHz is minimal for 5G NR comared with LTE… only about 10-15% in trials and possibly less in real-world implementation so far.

The waveform itself doesn't change very much from LTE in terms of relevant RF properties. The peak-to-average ratio of the RF signal is slightly higher, and by some anecdotal reports the 5G waveform is more difficult to achieve "crest factor reduction". Linearity requirements are basically the same as LTE, as these limits are tied to government limits and are not completely up to 3GPP.

Overall, the waveform itself is not very newsworthy. Massive MIMO and the bandwidth of the allocated frequency bands have more impact.

IMPACT OF MASSIVE MIMO

Massive MIMO demands a completely new RRH design, and the impact is significant on every component. Typical non-massive MIMO RRH units have included between 2 and 8 transceivers. Massive MIMO units so far use 32 or 64 transceivers (in macro base stations, which we define as working below 6 GHz). The reason for the increase is that we see significant benefits at the system level:

1. Multi-user MIMO can be more effective with large numbers of radio paths, allowing separate spatial streams for different groups of users.
2. Overall spectral efficiency is improved from roughly 2 bps/Hz to 6 bps/Hz if sufficient isolation between beams is achieved, allowing for re-use of spectrum within a sector.
3. Through software changes, the Massive MIMO system can be very flexible, allowing for very high level MIMO (8x8 or higher) in special cases, or allowing for flexibility in how the MU-MIMO is used.
4. Beamforming can improve the link budget, making 3-4 GHz signals travel as far (or farther) than signals below 1 GHz.
5. Antennas and radio elements are integrated, reducing loss and improving the overall link budget.

At the semiconductor level, the change to Massive MIMO drives some significant changes:

- Large numbers of transceivers alter the PA architecture. The power output from each radio is lower than before. A typical power level for a M-MIMO radio element at 3.5 GHz will be about 2 W average at the antenna (20W peak envelope power). The big ceramic PA packages are not necessary anymore. Instead, cheaper plastic packaging can be used.
- Antennas will be close together, forcing OEMs to cram the RF front ends into a small space. Each OEM has its own innovative way of placing the RF devices behind the antennas with attention to heat dissipation. At 3.5 GHz, each RF front end will have about 25 square centimeters of space.
- The planar layout of the antenna array has many OEMs thinking in terms of modular four-element sections. The ASICs, data converters, beamforming chips, and other devices are set up to handle four elements each, so that the RRH can be scaled up or down. The magic number of four elements is simply based on the simplicity of the layout.

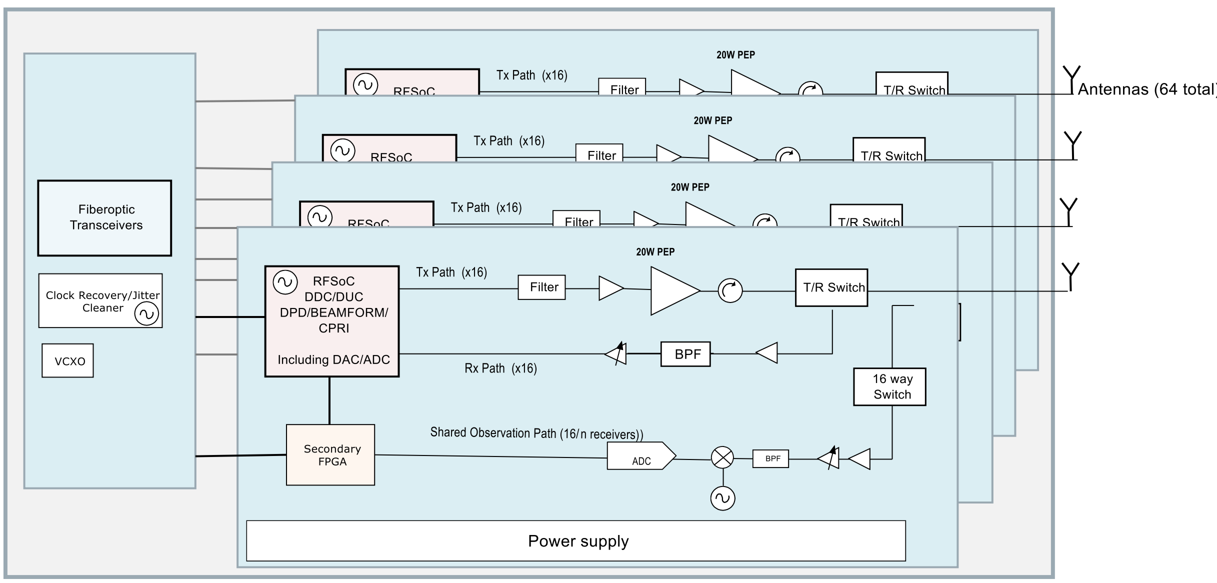

Figure 2 Block Diagram for a 64T Massive MIMO radio system

Source: Mobile Experts

Implementation of Beamforming

Two beamforming approaches are in development currently: Digital Beamforming and Hybrid Beamforming, where the actual phase/amplitude shift is done via analog components. Below 6 GHz, beamforming will be realized as an all-digital approach because the bandwidth of the signal will be narrow enough (50 to 100 MHz) that the digital signal processing will be realizable and practical.

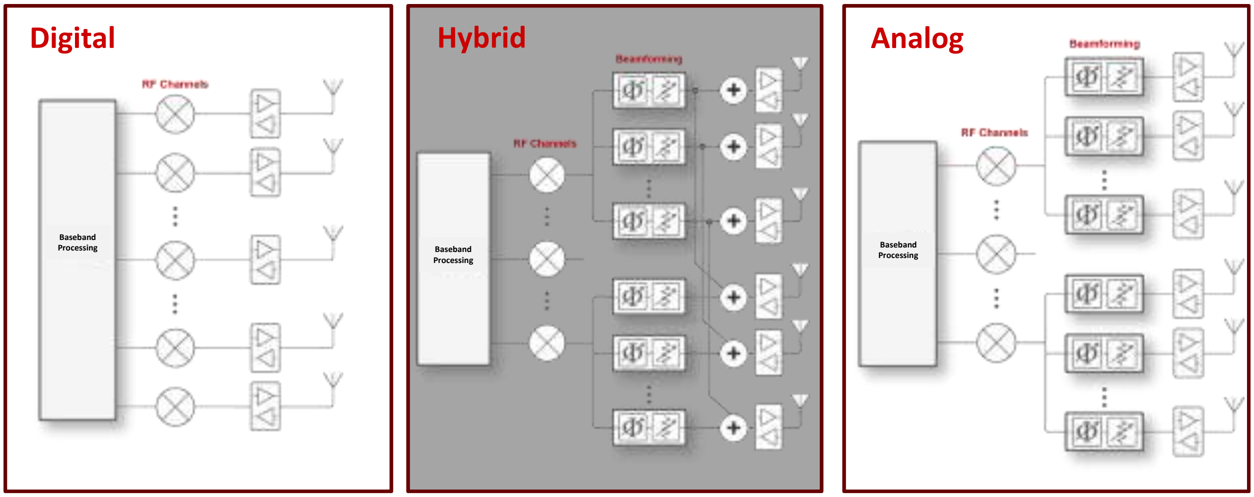

Figure 3. Block Diagrams for Analog, Digital, and Hybrid Beamforming

Source: Peregrine Semiconductor

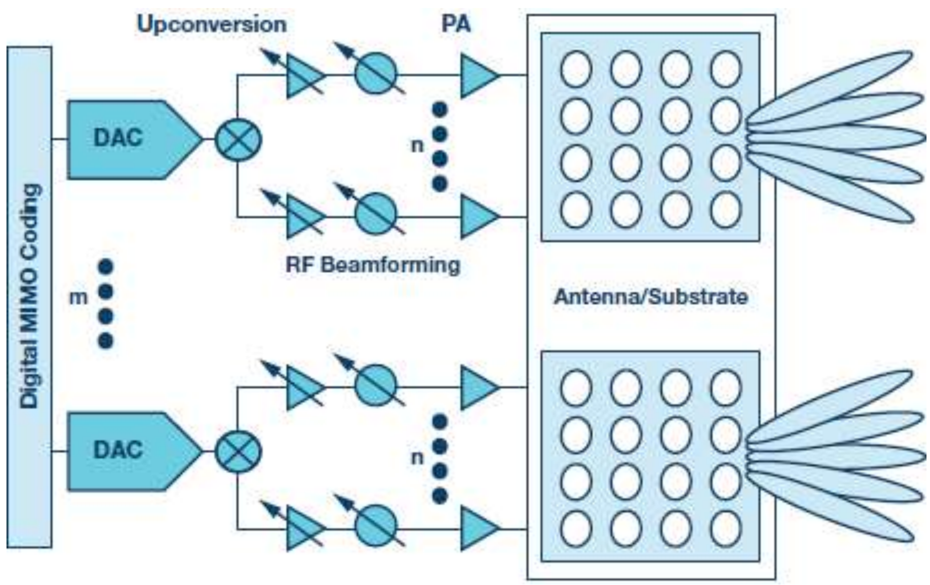

Figure 4. Hybrid Beamforming Diagram

Source: Analog Devices

Above 20 GHz, the hybrid beamforming approach will be used for the next few years due to bandwidth limitations in processing and power tradeoffs. The mm-wave implementation falls outside of the scope of this report but can be found in Mobile Experts' *5G Millimeter Wave 2019*.

WIDER CHANNEL BANDWIDTH

Radio bandwidth has grown from 200 kHz to 40 MHz over the past 20 years, and new '5G' bands represent another step. Most of these bands are set for a 100 MHz signal bandwidth for the radio. Given the ongoing advancements in CMOS technology, gate geometry has shrunk and the wider bandwidth is now both possible and economical.

In fact, the processors and data converters are now pushed by the mm-wave applications to bandwidth in the range of 1 GHz or even higher, so many of the standard products on the market now can easily handle the 100-200 MHz requirements of the sub-6 GHz macro market.

Wide bandwidth is generally more expensive, as data converters and DPD are stretched in has made it workable. Recent introduction of devices to cover 200 MHz channel bandwidth (with linearization over about 1 GHz) are now standard for the C-band 5G application.

Such wideband performance was considered extreme a few years ago, but as the ADCs and DACs drop down to lower process nodes, the bandwidth and spurious range performance are both met. It's now simply a question of cost optimization, where OEMs will try to limit the number of radio designs that they manufacture. Some 3-5 GHz radios will get a 200 MHz bandwidth even if only 100 MHz is required, simply to reduce the number of variations. Similarly, at mm-wave frequencies we expect a standard configuration for each OEM in the range of 800 MHz to 1 GHz bandwidth.

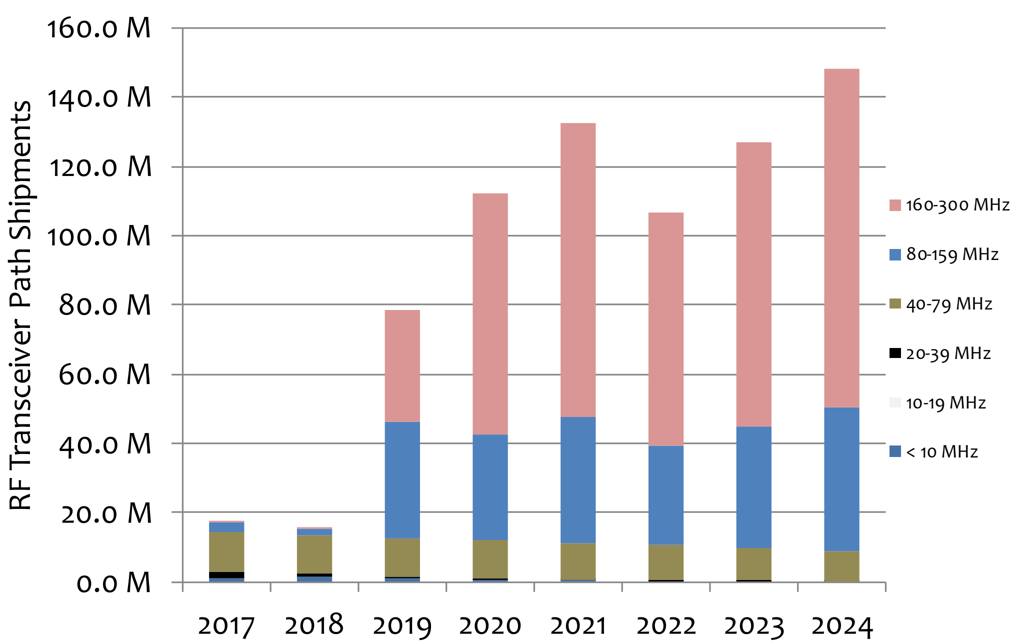

Chart 3: Transceiver shipments, by RF bandwidth supported, 2017-2024

Source: Mobile Experts

4 SEMICONDUCTOR TRENDS

FPGA VS ASIC: IT'S NOT SO SIMPLE ANYMORE

For the past 10 years, we have been tracking the tug-of-war between FPGA vendors and ASIC suppliers. New features are introduced on FPGAs, and as they become well understood they are typically hardened onto ASICs for lower cost and lower power. This ongoing back-and forth generally works in the favor of the FPGA vendors in the early days of a new generation, and then turns in favor of ASIC vendors for longer term steady production. Because new features are introduced constantly, the story has continued this way for years.

Now, new products are changing the discussion. Xilinx has introduced the Zynq family with an "RF System on Chip" capability, which integrates ARM cores for some processor functions (reducing cost and power), while keeping the programmable logic for new features such as beamforming which need the most flexibility.

At the same time, Xilinx has started to integrate the ADC and DAC functions into the RFSoC. This step eliminates the JESD204 interface, which consumes a lot of power. The power savings and size shrinkage are very compelling, especially for Massive MIMO radios.

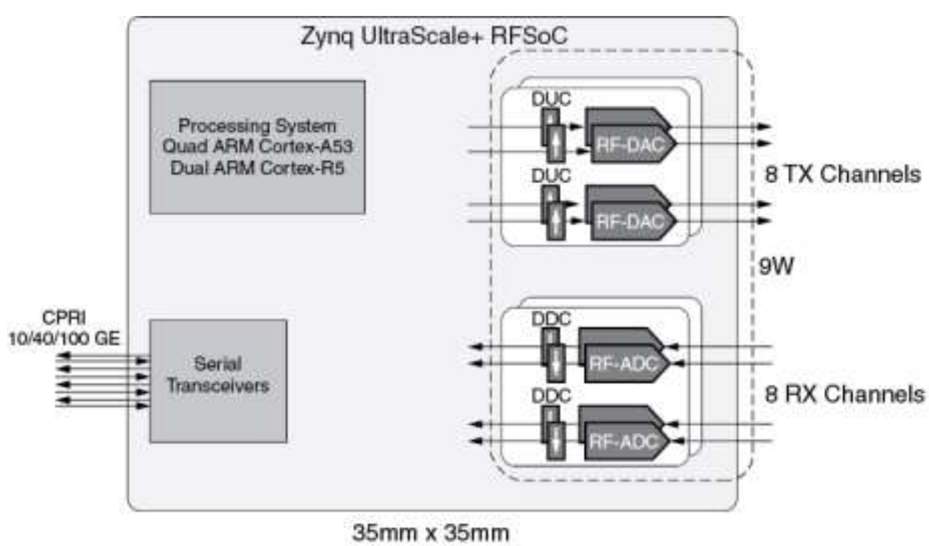

Figure 5. Integration of Processors and Data Converters

Source: Xilinx

Last year, we outlined two separate possibilities for integration:

The argument for ASICs and ADC/DAC integration with RF:
One group of vendors promoted the idea of ASIC development for the core DDC/DUC/CFR functions, with some integration of ADC and DAC with PLL and other RF functions to save space. This approach did not have the same level of power savings as the FPGA RFSoC but was more compatible with the ASIC path preferred by OEMs.

The argument for FPGAs/SoCs:
The integration of FPGA fabric with ARM Cores plus ADC/DAC functions eliminated a great deal of power consumption, also reducing the footprint on the PCB. The savings comes out to roughly 1 W for each JESD204 lane. In the case of 64T massive MIMO, this can be more than 60W of power savings, out of a total heat dissipation budget of 250W.

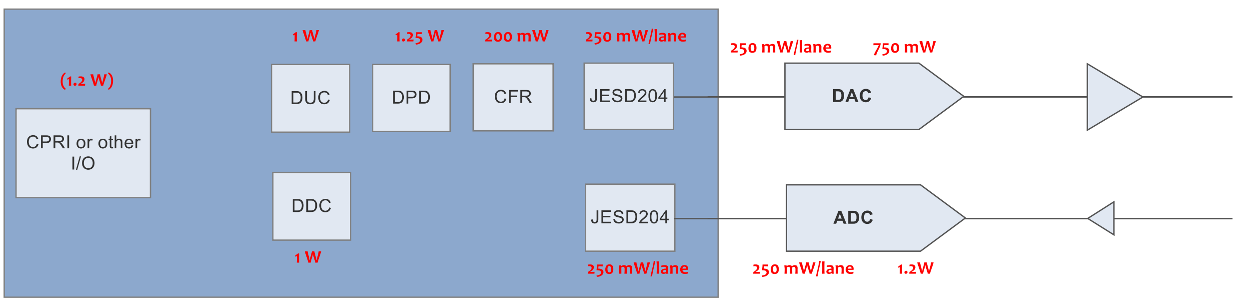

Figure 6 Power Consumption by Function in a Discrete 5G transceiver

Source: Mobile Experts

Note: Power consumption shown for a 100 MHz BW for a single transceiver chain. JESD204B power is broken out separately from ADC/DAC power.

We've had some interesting developments in the market as well. For example, Intel has acquired eASIC, giving Intel the capability to provide ASICs with rapid response time, in addition to their Altera FPGA-based products. The number of mobile-savvy ASIC suppliers is thin, so this will be a way for Intel to play in the in-between space where FPGA based development moves into production. The eASIC approach can be quicker and cheaper than other ASIC options for a lower volume opportunity.

Architectural Trends: Integration of DFE and ADC/DAC

Xilinx has introduced SoCs that include ARM cores and FPGA fabric in order to achieve multi-core processing for the remote radio head. The high-level philosophy of the Xilinx architecture is to support multiple product configurations with a flexible radio design, using the ARM cores and FPGA programmability to adapt to variations in things like:

- Impact of frequency band/bandwidth on DPD
- Impact of frequency band/bandwidth on beamforming;
- Impact of Envelope Tracking in the design on RF characteristics;
- Different MIMO configurations that require variations in sharing observation paths and sniffer receivers;

> In the Xilinx paradigm, the most important problem to solve is the power consumption of the JESD204 interface….so they are proposing integration of the data converters with the digital front end, in order to reduce the JESD204B processing dramatically.

Each JESD204B lane burns about 250 mW to serialize/deserialize the data, so the total power impact is significant at about 500 mW per lane. A 100 MHz transceiver would be likely to use a four-lane configuration, and of course for 4T4R configuration the total power would be quadrupled for a total of 8 W. Xilinx integrates the digital front end (DUC, DDC, DPD) with the ADC and DAC to eliminate the overhead in power consumption.

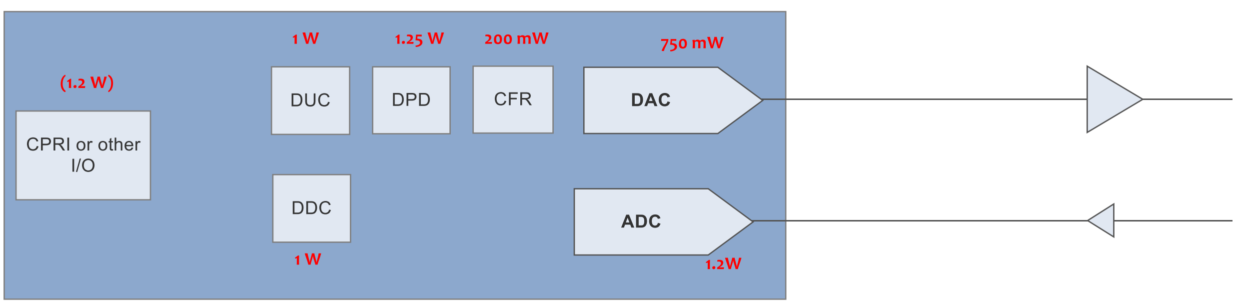

Figure 7 Power Consumption Impact of DFE/Data Converter Integration

Source: Mobile Experts

Note: Power consumption shown for a 100 MHz BW for a single transceiver chain.

The Xilinx approach achieves significant power and size savings, and we believe that major OEMs will choose this architecture for product configurations that don't reach the volume to justify ASIC development. For the mainstream 64T radio at 3.5 GHz in China, expect ASIC dominance to drive OEMs toward different integration strategies. But for the FDD bands, with major differences in DPD and beamforming, we expect to see these RFSoCs appear.

So far, in the mainstream Massive MIMO applications, Xilinx has been the winner. To our knowledge, all of the top OEMs are using the Xilinx RFSoC for massive MIMO processor/data converter applications, while retaining the more discrete approach for FDD implementation and other possibilities such as Envelope Tracking.

One more note on FDD: Integration of ADC/DAC with RF devices such as up/downconversion or quadrature modulators is a real possibility. PMC/Sierra initiated this concept years ago, and it's continued by Maxlinear, and now TI and Analog Devices offer similar possibilities. In the FDD block diagram this is still a distinct possibility.

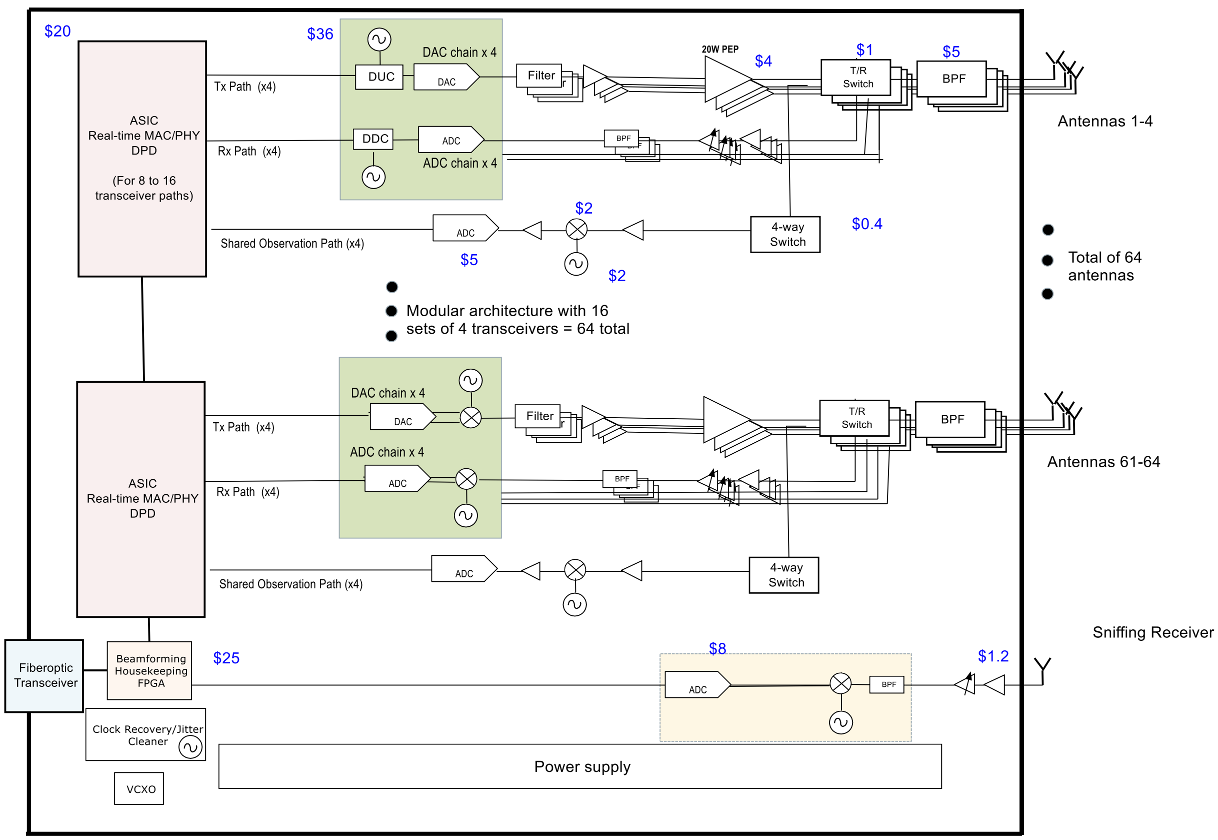

Figure 8 Massive MIMO block diagram in TDD without RFSoC integration

Source: Mobile Experts

EVOLUTION OF THE FDD BLOCK DIAGRAM

A typical FDD remote radio head is a 4x40W subsystem, with a lot of discrete devices. This area of engineering is not changing as fast as the Massive MIMO market, and in fact most of this block diagram is the same as last year. We have simply updated to show that the four ADCs and DACs are typically packaged together as a single product for this 4x application. ASICs are used pretty widely in the FDD market, as no beamforming or other new flexibility is required.

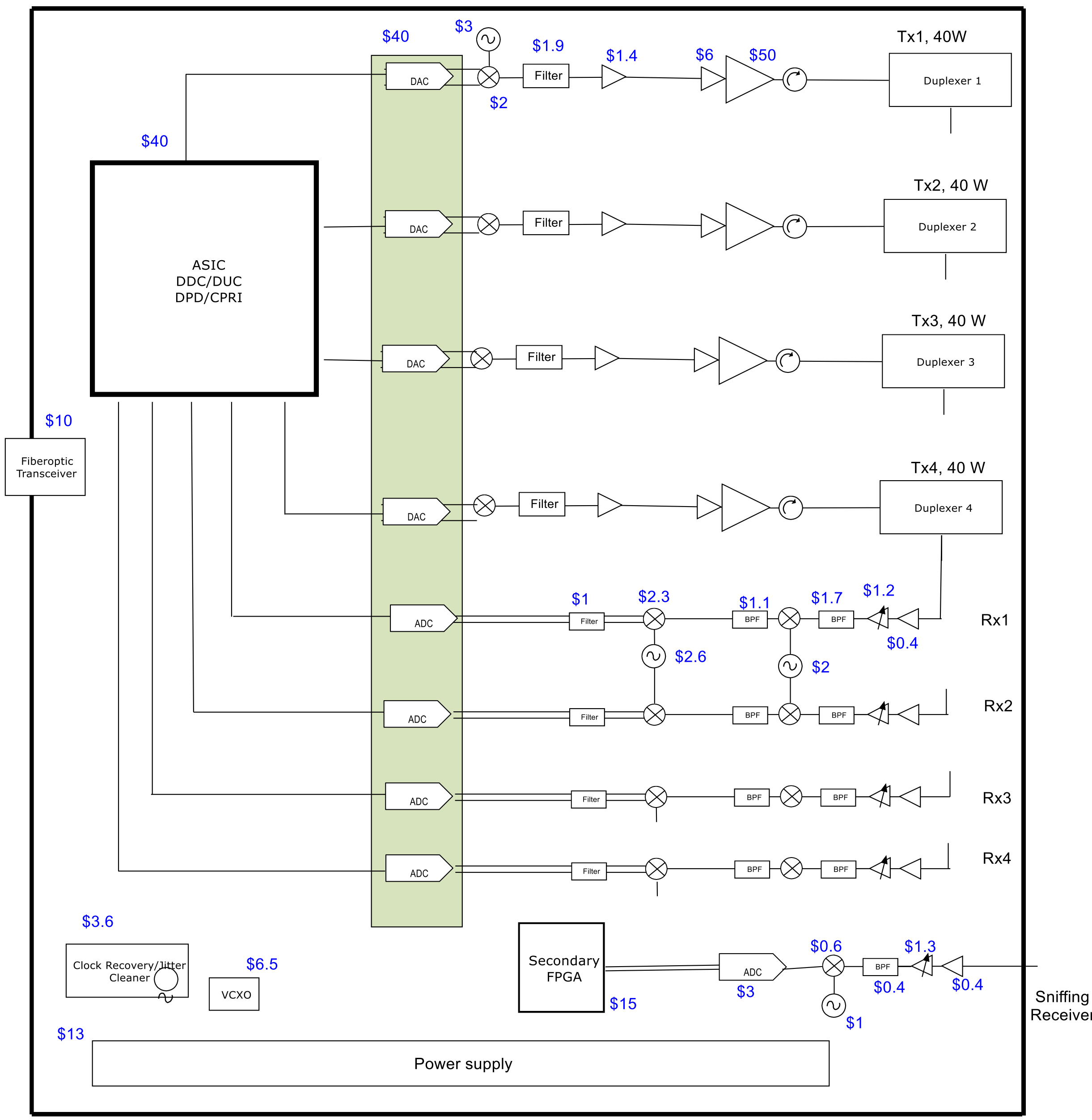

Figure 9   Dollar Content for Each Component in a 4x40W FDD RRH/ASIC configuration

Source: Mobile Experts   Note: Assuming 2019 production volume of about 1M units, and narrow bandwidth (20 MHz)

In the 2 GHz FDD bands, we will see some 5G Massive MIMO upgrades over time. The volume will be relatively low compared with TDD systems, but the benefits of Massive MIMO will still justify its use in the 1800 band and other wideband applications.

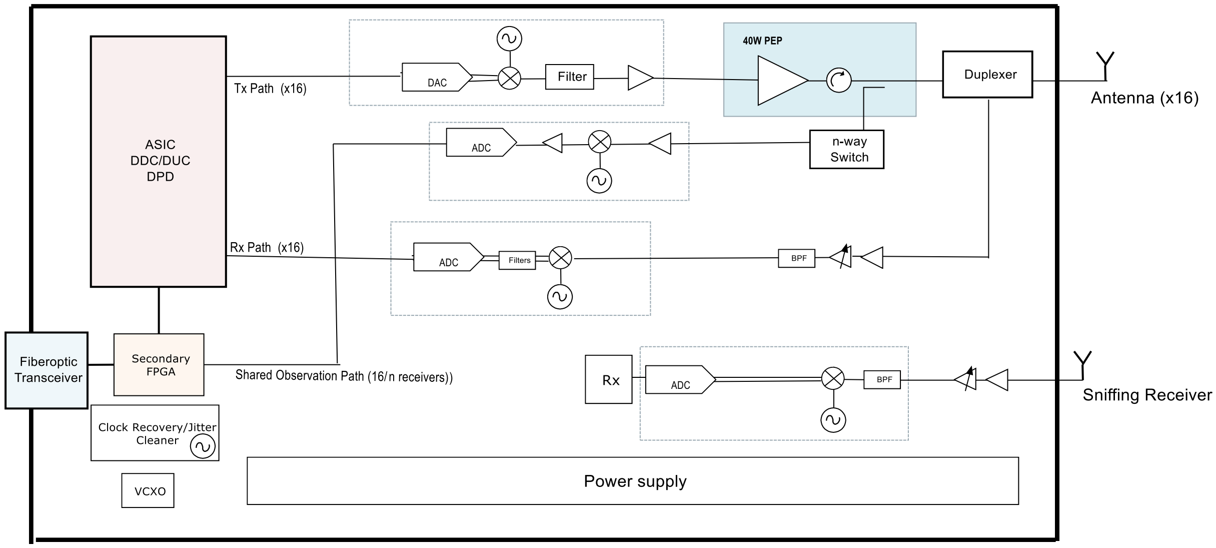

Figure 10 Massive MIMO 16T16R block diagram in FDD

Source: Mobile Experts

DISCRETE POWER TRANSISTORS VS INTEGRATED RF MODULES

Discrete RF power amplifiers are still the main choice in the market for massive MIMO and for other applications. Substantial development has come together over the past three years, so that PA vendors are ready to integrate the RF amplifier with couplers, LNAs, switches or other functions. But massive MIMO is too new. The OEMs don't want to commit to integration on this kind of critical component, because there are likely to be changes for field optimization. We're setting aside the possibility of integrated RF front end modules until next year.

We don't expect to see the integration shown in blue below until about 2021, because the OEMs will be starting with discrete devices for highest flexibility. However we believe that RF integration benefits (from non-50 ohm match and close proximity) will drive the industry toward these modules over time.

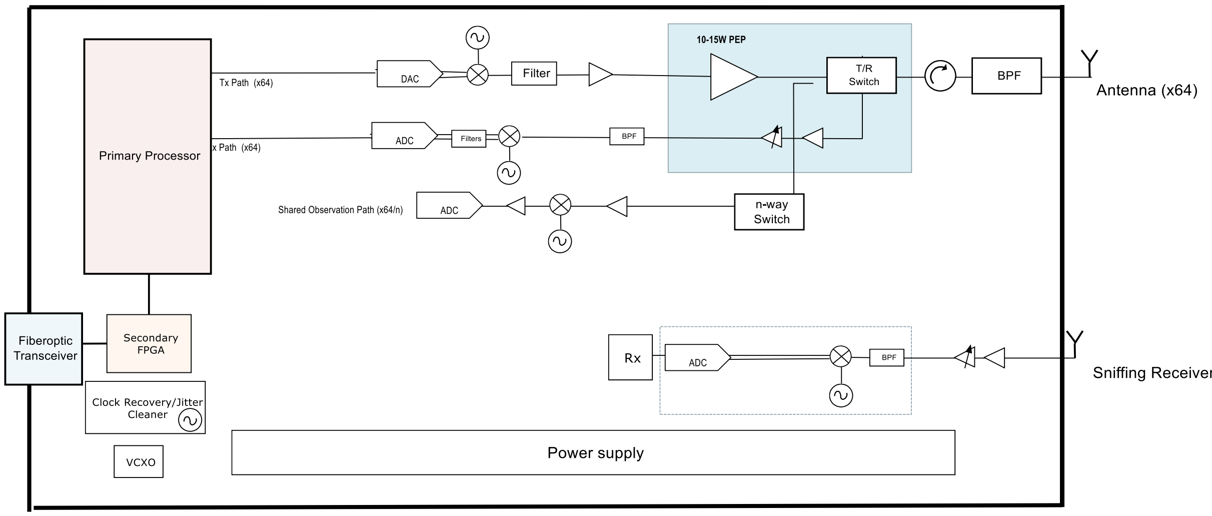

Figure 11   Expected use of Front End Modules for the PA in 3.5 GHz Massive MIMO

Source: Mobile Experts. Power Amplifier FEM shown in blue.

POWER AMPLIFIERS

GaN is steadily gaining in market share, with high power density and high efficiency for the same linearity/power as LDMOS. However, LDMOS performs quite well at a cheaper price, even at 3.5 GHz, for low power applications, so LDMOS suppliers remain right there in the production volume for Massive MIMO.

One major change for the PA is that, with massive MIMO, 64 separate PAs are used instead of 2-4 large PAs. This means that the packaging can get much cheaper, linearity/DPD requirements are simpler, and the cost target is much lower. All major vendors have answers to those questions.

2Q2019

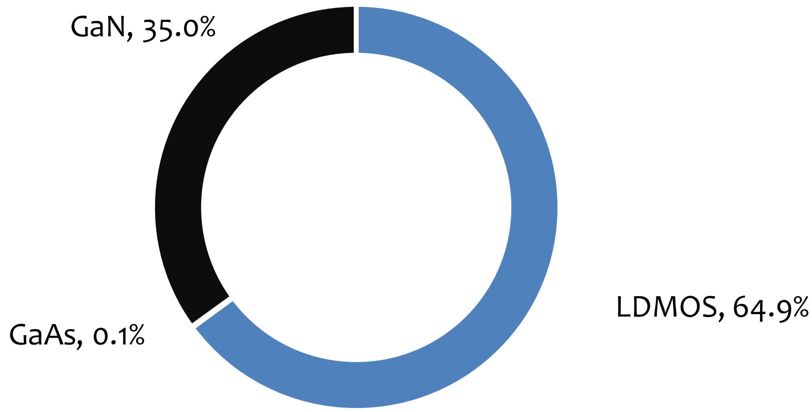

Chart 4: Power Transistor Shipments, Breakdown by Semiconductor Process Used

Source: Mobile Experts

Asymmetric Doherty architectures are table stakes in the high power RRH market, as they can achieve the best balance of linearity, efficiency, power, and cost. So far, all major OEMs have stuck with this approach and they have not taken steps to move integrated front-end modules (PA/Switch/LNA) into production.

Sooner or later, the market will move into Front End Modules. For 3.5 GHz Massive MIMO applications, the OEMs have all asked about integration of PA/switch/LNA functions, but all indications are that this step won't be taken this year, or at least through mid-2020. There are too many unknowns which could change in terms of power levels or isolation values or other factors, so discrete devices are a lower risk option for now. Our current view is that the FEM will arrive in the C-Band mMIMO case in roughly 2021.

NXP has been the clear leader in market share for a long time, with Ampleon in second place. Sumitomo and Wolfspeed have established a much stronger presence and are on a stronger growth curve using GaN technology. This year, Qorvo has also arrived on the scene with significant shipments to Huawei (at least prior to the shutdown in May 2019).

Infineon and Wolfspeed/CREE are now counted as a single company, and we track RFHIC as a separate company despite their current use of the CREE fab.

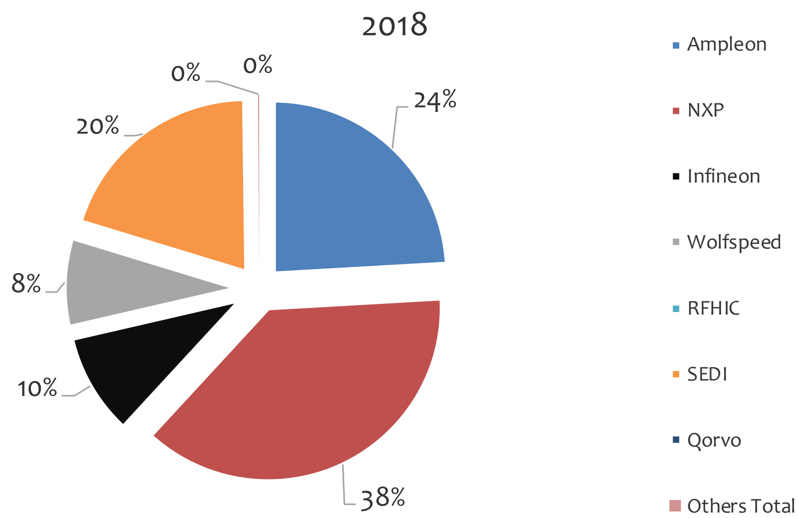

Chart 5: Power Transistor Market Shares, 2018

Source: Mobile Experts

The first half of 2019 has not been normal at all, as Huawei has bought roughly 20 million LDMOS and GaN power devices in excess of their production requirements… then during May, some US suppliers were forced to stop their shipments.

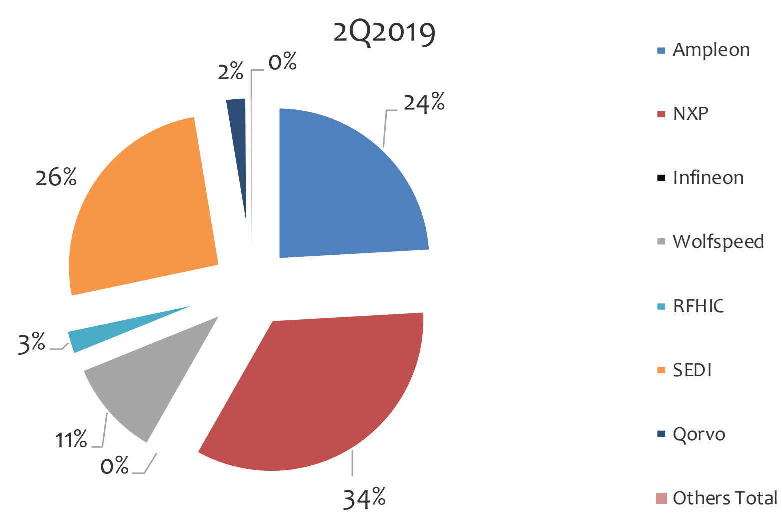

Chart 6: Power Transistor Market Shares, 2Q2019

Source: Mobile Experts

FPGAs, ASICs, and RFSoCs

In the previous section on technology trends we have already covered the major thrust toward RFSOC integration: It's all about reducing power consumption, cost, and size on the board.

The top four OEMs now use ASICs routinely in production FDD and TDD LTE base stations. All four have the volume to justify the ASIC, and the LTE application is stable enough to converge all customers onto a common ASIC platform. The economics of ASICs work out that volume over about 100,000 units per year justifies the expense of developing an ASIC. Huawei, ZTE, Ericsson, and Nokia all have product lines that meet this level of volume.

As we move into 5G, for FDD applications the architecture looks very similar to the LTE case, and is a simple migration of the ASIC design. For the radio functions (upconversion, downconversion, DPD, etc) the 4G and 5G waveforms are similar and the existing product line will be extended.   However, in the TDD case we typically have enough bandwidth to justify Massive MIMO, leading to the RFSoC architecture.

For the early 5G Massive MIMO ramp, all of the top base station vendors are using the Xilinx RFSoC product, taking advantage of the low-power integration.   The question now is: How long will Xilinx be able to control this market, as all of their customers would prefer to migrate to a cheaper ASIC?   The pressure is on, because volume is growing very quickly to the 100,000+ radio level that justifies ASIC investment.

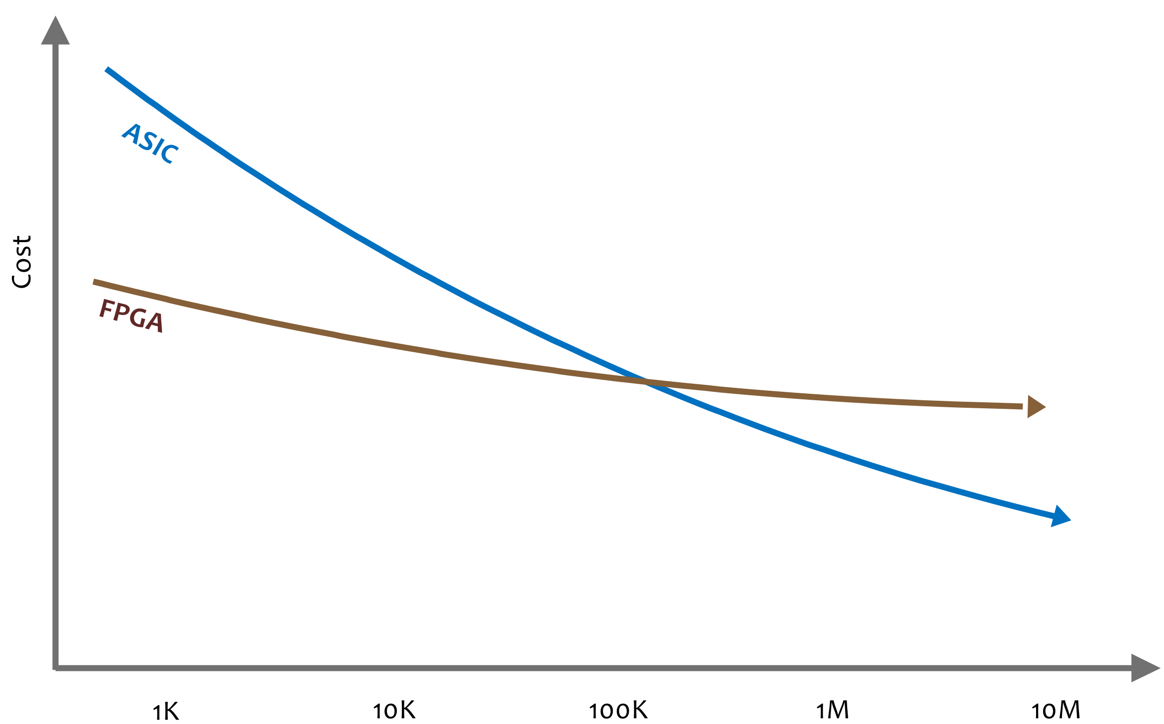

Figure 12   Tradeoff between ASIC and FPGA

Source: Mobile Experts

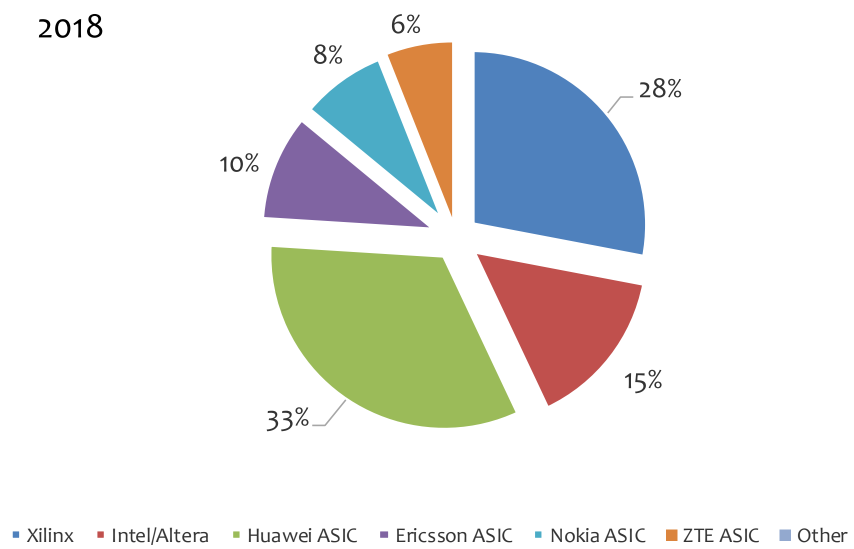

Chart 7: FPGA/ASIC primary processor market shares in RRH, 2018

Source: Mobile Experts

In most RRH designs, a second processor is also used for "secondary" functions, including DPD adaptation, Serdes communication, and basic housekeeping. New active antenna systems will also use the FPGA for beamforming calculations. All of these features are difficult to harden in an ASIC because of the wide variation in operating parameters. A simple FPGA or mid-tier FPGA is often the right solution, with the choice depending on the level of computation that is necessary.

Secondary processors are likely to be with us for a long time. The OEMs have little interest in rolling every last feature into the ASIC, so they will simply try to manage the size/cost of the secondary FPGA to keep the cost as low as possible.

Market shares are pretty simple because Xilinx and Intel/Altera dominate the market for big full-featured FPGA devices. Lattice also participates in this market without putting as much of their own effort into software solutions such as DPD and beamforming…performing the housekeeping function efficiently.

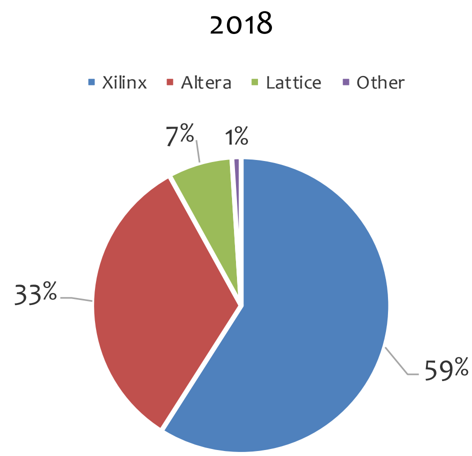

Chart 8: Secondary Processor Market Shares, 2018

Source: Mobile Experts

LINEARIZATION SOLUTIONS

Digital PreDistortion (DPD) is standard through the industry, and every OEM has advanced proprietary algorithms to maximize the correction. We see the DPD algorithms as fairly stable for FDD applications where the 4x40W, 4x60W, or 4x80W power amplifiers are operating at a high level. In these cases, the focus remains on maximizing linearization through Crest Factor Reduction (CFR) and asymmetric Doherty PAs, with DPD algorithms optimized by each vendor in their own way.

At lower power—for example, in massive MIMO cases—the linearization requirement is not as extreme, due simply to the lower power of the amplifier and its naturally higher linearity. Instead of 30 dB of correction, the OEM might be happy with 20 dB or possibly less. This opens up the opportunity for alternatives. In these cases, we are seeing "light" DPD solutions built into the firmware on the Xilinx RFSoC.

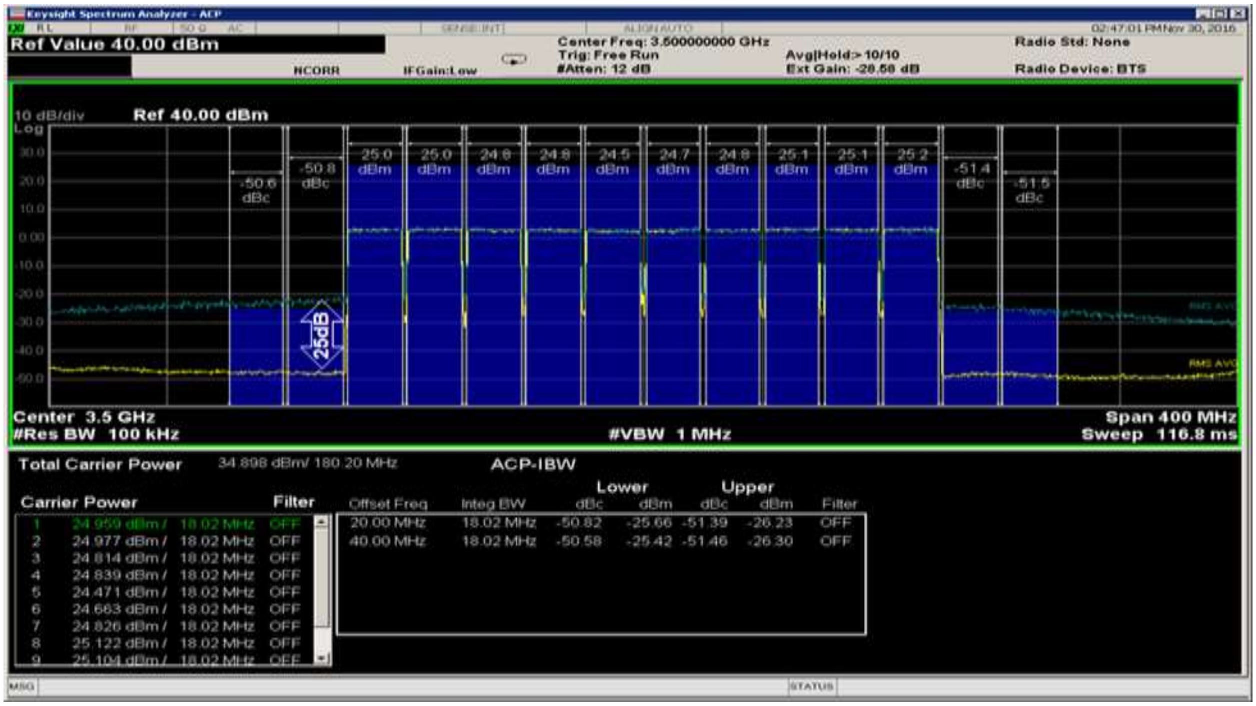

Figure 13 Linearization performance over 200 MHz bandwidth using NanoSemi DPD

Source: NanoSemi

ANALOG-TO-DIGITAL CONVERTERS (ADCS)

Despite the integration in the RFSoC, we're still tracking ADCs and DACs as separate devices, because outside of Massive MIMO we see 'discrete' ADCs and DACs as the ongoing solution. (Note that we should clarify: Discrete ADCs and DACs means that they are not integrated with the processor, but they are often integrated into bundles of 2-4 ADCs and DACs in one package, along with PLLs, buffer amplifiers and other RF functions..

Technology has advanced quickly in ADCs, as bandwidth has increased from 40-60 MHz for LTE to hundreds of MHz in the case of 5G. Resolution and dynamic range cannot be sacrificed, so as bandwidth gets wider these devices are challenging. The vendors have moved down to the next process node, taking advantage of Moore's Law to drive up to 4 Gsps along with high performance on the analog side.

Texas Instruments and Analog Devices are both very strong vendors in this area, and the key competition between these two runs along the lines of which company can integrate RF functions effectively at low cost, shaving off power consumption and shrinking the size of the line-up to fit into a massive MIMO slot.

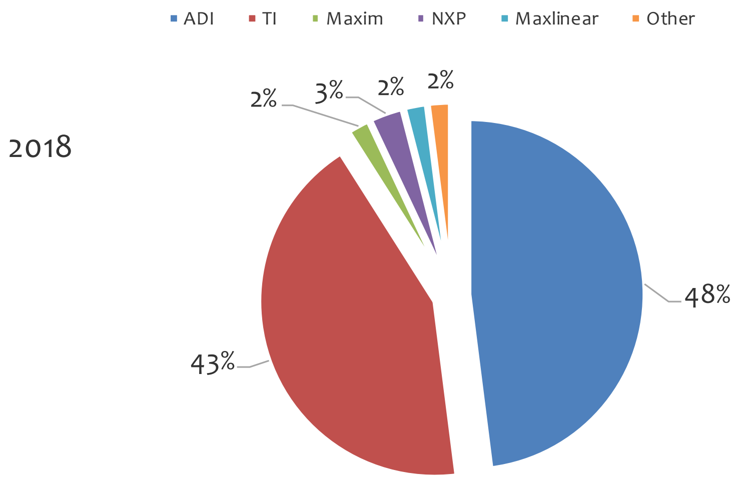

Chart 9: Analog-to-Digital (ADC) market shares, 2018

Source: Mobile Experts

It's notable that while Xilinx wireless communications revenue shot up over the past 9 months, Analog Devices and TI have continued to talk about the potential of 5G for higher content, without substantially higher revenue. This is our indication that ADI and TI have missed out on the dollar content growth associated with massive MIMO, at least for the early ramps in Korea and China.

However, ADI and TI control the market for these discrete data converters, and the discrete market is not going away. Both companies have strong relationships with all of the major base station OEMs. Other vendors have niche shares and some have dropped out (Linear Tech) as the macro infrastructure market continues to mature. PMC-Sierra's product line was acquired by Maxlinear, and has not taken off in 5G yet… but will have another shot when OEMs return to 5G with their ASICs and want an integrated transceiver.

Digital-to-Analog Converters (DACs)

While ADCs remain on 12-bit resolutions, DACs are generally at 14 bit resolution to support linear performance over wide bands. Effective DPD linearization involves a wider bandwidth than the RF signal itself, so DAC performance and cost depends dramatically on signal bandwidth. This means that stepping up to 100-200 MHz transmitters will drive a step from hundreds of Megasamples per second to over 1 Gsps. Spurious free dynamic range of at least -85 dBc is common for LTE implementation.

For LTE and for upcoming 5G FDD applications, DACs are now sold in quad-channel units with both ADCs and DACs integrated together. In some cases, reference oscillators are integrated with DACs in order to optimize the phase noise performance of the resulting output signal.   Also, in some cases (Maxlinear), the quadrature modulator is included with the DAC for a more highly integrated implementation.

For TDD designs, we see the OEMs migrating toward integration of ADC and DAC, including modules with four channels in a single package.   In this way, the ADC and DAC markets will merge and the friendly situation over the past few years (where ADI led in ADCs and TI led in DACs) will become a bit more competitive.

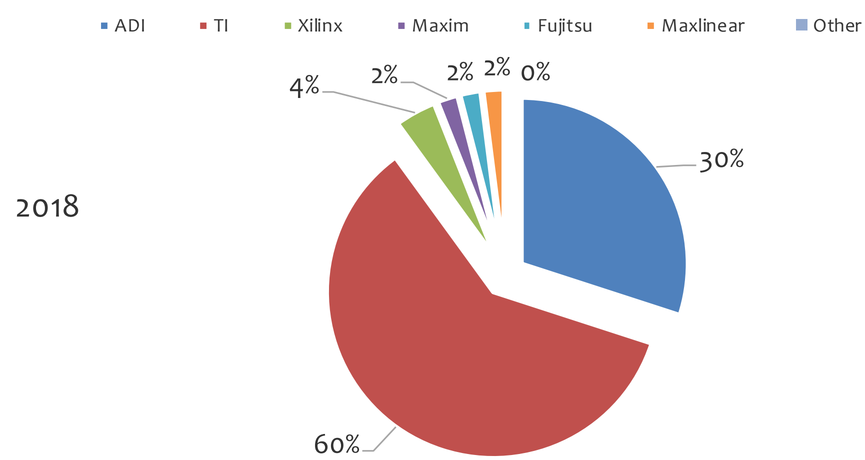

Chart 10:   Digital-to-Analog (DAC) market shares, 2018

Source: Mobile Experts

PLLs, VCOs, Timing Reference

The discrete timing/PLL market is gradually retreating as many of the PLLs supporting the main signal chain are integrated into ADC/DAC products or RFSoCs. However, there are still high level timing and frequency reference devices needed to clean up the master timing source—which typically comes over the CPRI link or from GPS.

The tight phase noise requirements of 5G radios could drive ongoing requirements for discrete oscillators and PLL devices… but we're likely to see one per radio box, so the market for these devices will not scale up with Massive MIMO as other devices do.

As we track market share for PLL and timing components, we're lumping multiple items together. The PLLs will be integrated with other components in some cases, but the discrete VCXOs and possible OCXOs are generally separate from the main RF chain. The market share chart is a compilation of multiple devices to show the important players in this general area.

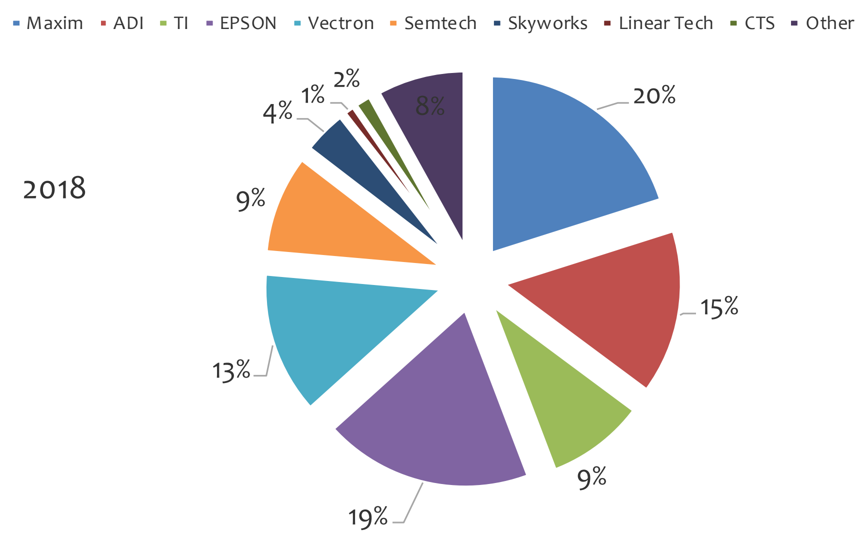

Chart 11: PLL/Timing market shares in RRH, 2018

Source: Mobile Experts

SMALL-SIGNAL RF COMPONENTS

The move to Massive MIMO expands the opportunity for some small-signal devices such as LNAs. Instead of four LNA paths per RRH, now we have 64 (plus sniffer receivers and other extras). Other devices, such as quad modulators, phase shifters, and step attenuators may disappear from the market as they are integrated into more advanced ADC/DAC transceiver modules, but a few key discrete components will remain where performance is still considered critical.

Still, the RF market is still thriving as new functions are added such as observation receivers, sniffer receivers, and calibration paths. These additional functions add amplifiers, filters, modulators, and other simple RF devices in multiple places around the transmitter and receiver chains. These components condition the signals in the receiver and transmitter chains to be free of interference and at the right power level and frequency to interface easily with the digital/mixed signal devices. For the sniffer/observation paths, discrete implementation still remains the most flexible way to implement the extra functions in multiple base station products.

Because many different semiconductor/other process technologies are used in the RF area, many different companies play in this fragmented market. These products are pretty stable with long product life cycles. Key suppliers include ADI, Broadcom, CTS, Fujitsu, Maxim, Mini-Circuits, Qorvo, Murata, Skyworks, and several others. In each of their specialty areas, these companies can meet the required dynamic range, noise figure, phase noise, or other performance characteristics in the radio head.

QUADRATURE MODULATORS

Most base station transceiver designs since about 2000 involve direct conversion transmit chains and zero-IF or low-IF receivers, so discrete mixers have given way to either digital or analog quadrature modulator products. The FDD market (with lower levels of MIMO) will continue to use more discrete quad modulator products, but the TDD market is moving toward higher levels of integration, especially in support of 64T64R mMIMO systems and higher, where size and component count get unmanageable.

AMPLIFIERS, ATTENUATORS, FILTERS, DIODES, DISCRETE PHASE SHIFTERS

Several small-signal devices are used through the transmitter and receiver chains, including SiGe, GaAs and silicon amplifiers, SAW and BAW filters, GaAs and BiCMOS switches, PIN diodes, and others. The wide variety of process technologies used for high dynamic range results in the coexistence of 10 or more process technologies in one transceiver.

Some of these functions are being absorbed by CMOS, but it's always a tradeoff of cost reduction and performance. CMOS keeps improving with lower process nodes, so gradually the amplifiers, phase shifters, and other devices are gobbled up by integrated transceiver modules. But we expect that certain components such as LNAs, high power switches, and filters will simply never be integratable on CMOS.

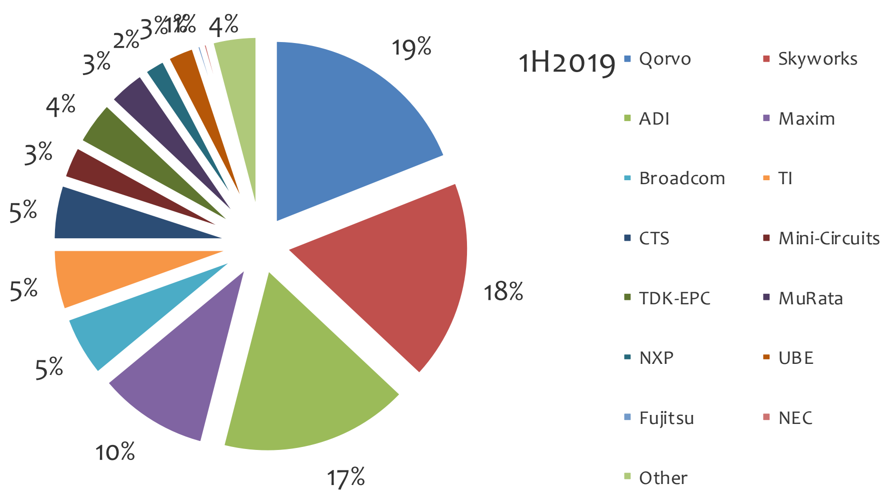

Chart 12: Small Signal RF Market Shares in RRH, 1H2019

Source: Mobile Experts

1H2019 share			
Small Signal	Mobile Infra. Revenue		Products
Qorvo	$47.9M	19%	VGAs, filters, switches
Skyworks	$45.4M	18%	Amplifiers, switches, circulator, filter
ADI	$42.8M	17%	Amplifiers, detectors,
Maxim	$25.2M	10%	Amplifiers, buffer amps, detectors
Broadcom	$13.9M	6%	LNAs, switches
TI	$13.9M	6%	Buffer amps
CTS	$12.6M	5%	Filters
Mini-Circuits	$7.6M	3%	Miscellaneous
TDK-EPC	$10.1M	4%	Filters
MuRata	$8.6M	3%	Filters, DSAs
NXP	$5.0M	2%	Pre-driver Amplifiers
UBE	$6.3M	3%	Filters
Fujitsu	$1.3M	1%	Switches
NEC	$1.3M	1%	Switches
Other	$10.3M	4%	
TOTAL	**$252.0M**	**100%**	

Figure 14 Table of Small Signal RF Vendors and Macro RRH revenue

Source: Mobile Experts

5 EQUIPMENT AND SEMICONDUCTOR OUTLOOK

System Level Mobile Infrastructure trends

The 5G ramp is here! Korea and China are now moving along briskly to deploy nationwide 5G, and other countries such as Estonia, Finland, Japan, and others are contributing as well. Some other countries are lagging behind, or using different frequency bands. For example, the United States does not have much new 5G spectrum below 6 GHz, so the bigger operators are deploying infrastructure above 20 GHz. We expect that, over the next 3 years or so, the US market will come together with the T-Mobile/Sprint merger, CBRS, and new C-Band spectrum providing avenues for investment.

The biggest wild card here is China. The licenses for 5G at 2.5 through 4.9 GHz have been issued in China, and all three operators have started their deployments. China Mobile is likely to be the first to deploy large numbers of 5G base stations. They started in January 2019 and with the official licenses in June 2019 we expect the second half to involve tens of thousands of sites. According to one rule by the Chinese MIIT, each operator is expected to deploy 1 million 5G base stations by June 2021, but we are hesitant to make that a firm forecast based on political uncertainties.

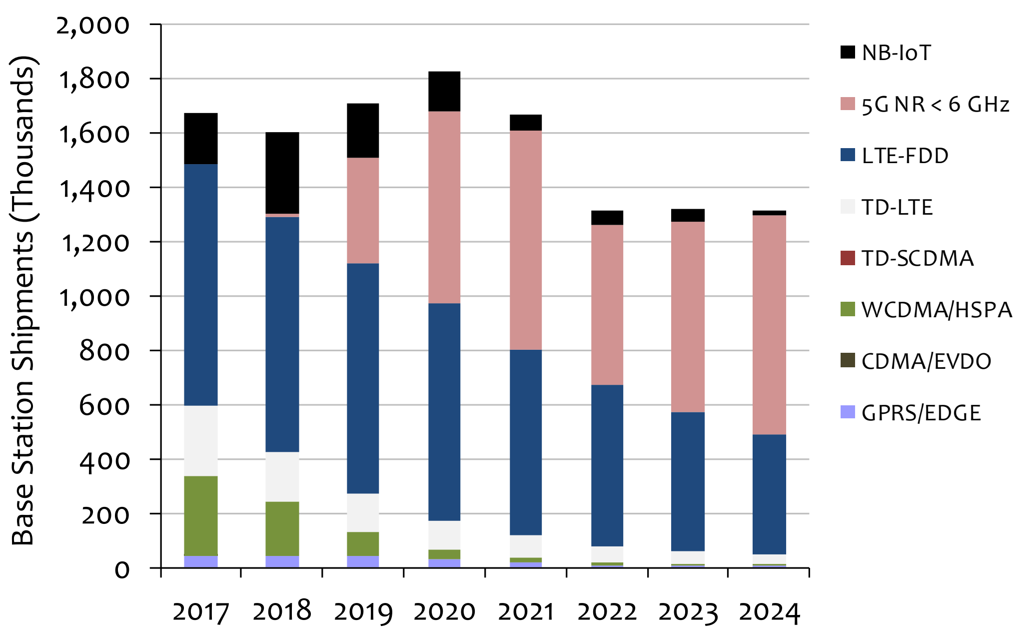

Chart 13: Global base station shipments, by air interface standard 2017-2024

Source: Mobile Experts (From Macro Base Station Transceivers Forecast, July 2019), assuming about 600K base stations per operator in China

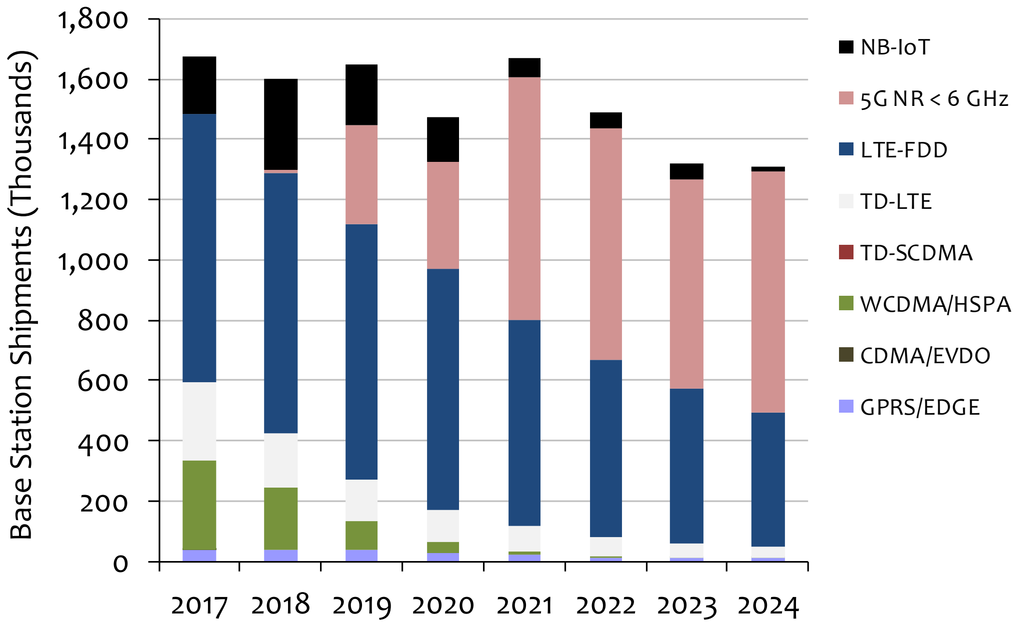

Chart 14: Global base station shipments, by air interface standard 2017-2024

Source: Mobile Experts (From Macro Base Station Transceivers Forecast, July 2019), assuming Huawei component access remains cut off through November 2020

Note that if the political situation between the USA and Huawei/China is not resolved quickly, then we expect the ramp in China to be delayed. If the current standoff status persists through November 2020 (the USA election), then we believe that the Chinese government will reset the 5G timing to spread their deployment over 5+ years.

Definitions: Mobile Experts counts each physical transmitter/receiver set as a transceiver, so that two transceivers are used in 2x2 MIMO. A 64T64R active antenna system is counted as 64 transceivers.

As a result, the chart for transceiver shipments is dramatically different than the view of 'base station' shipments. Instead of another decline in the market after 2020, the RF market shows strength throughout our 5-year forecast.

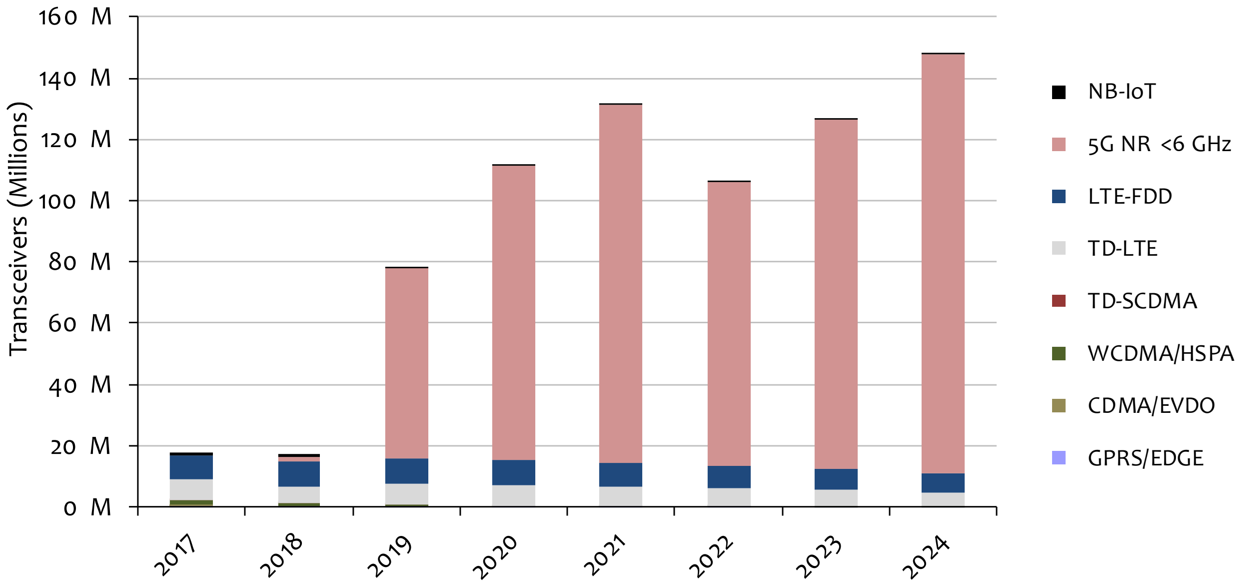

Chart 15: Global Macro Transceiver Shipments, 2017-2024

Source: Mobile Experts (From Macro Base Station Transceivers forecast, July 2019)

RRH SEMICONDUCTOR OUTLOOK FOR MACRO INFRASTRUCTURE

The growth of RF content in Massive MIMO will have a dramatic impact on the RRH Semiconductor market, with multiple segments doubling in size. In particular, the RFSoC and amplifier segments stand to gain substantially in this market shift.

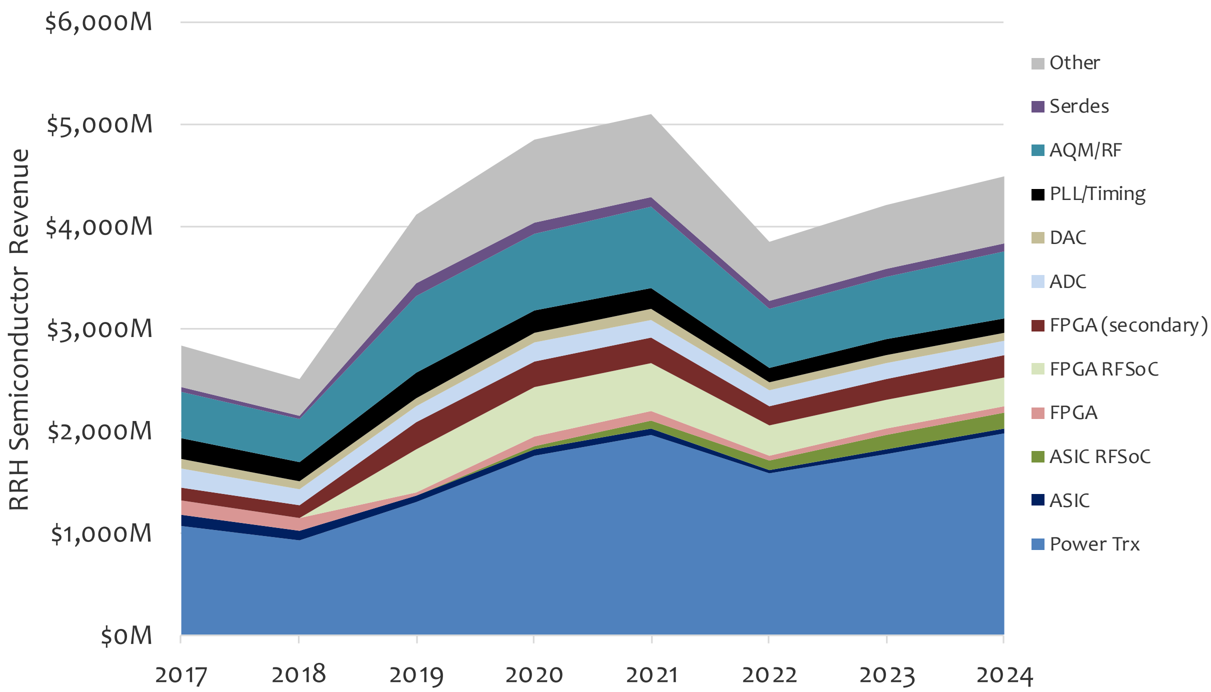

Chart 16: Global Semiconductor Market for RRH, 2017-2024

Source: Mobile Experts

POWER TRANSISTOR OUTLOOK

The first half of 2019 has been a steep ramp for power amplifiers, as Huawei has pushed its vendors extremely hard to expand their capacity and to ship as many devices as possible. We estimate that during the first six months of 2019, Huawei bought 20 million more power transistors for massive MIMO than they needed, in anticipation of a shipment shutdown. They are still buying from Japan (SEDI) and Europe (Ampleon), so this bubble of inventory remains in place.

Meanwhile, at the radio level the shipments are ramping up now, so we anticipate a strong year in 2019 overall, followed by even stronger production in 2020 and 2021. In short, the market for LDMOS/GaN power amplifiers will roughly double in this 5G surge, with 4X growth in the number of devices shipped.

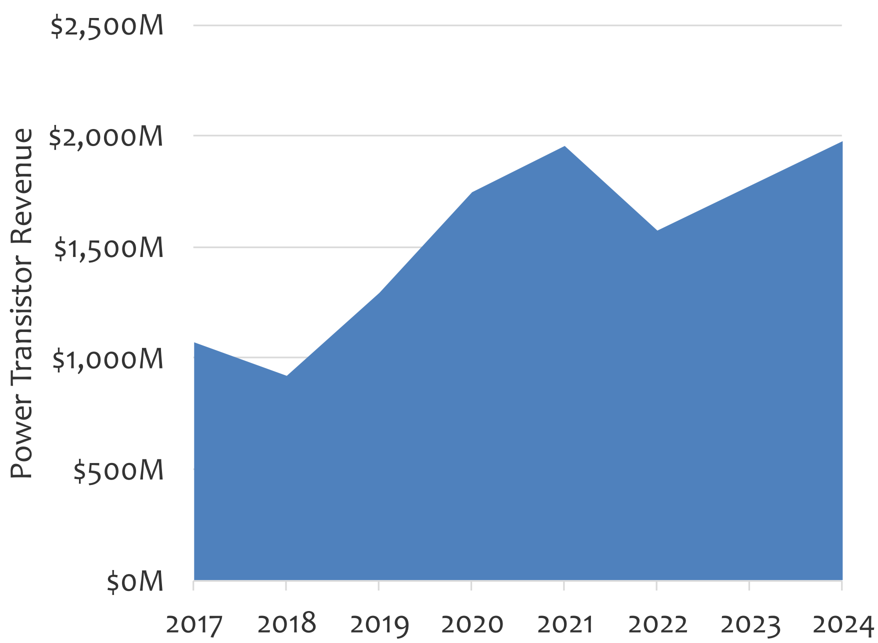

Chart 17: Power Transistor Market for RRH, 2017-2024

Source: Mobile Experts

For Massive MIMO, both LDMOS devices and GaN devices will work. GaN is now available in plastic packages for massive MIMO systems, the cost of GaN is considered acceptable, even though it's still a bit more expensive than LDMOS. For the higher power requirements above 2.5 GHz, we expect GaN to dominate the market, but for the 64T and 32T market, LDMOS appears to have competitive performance and lower cost.

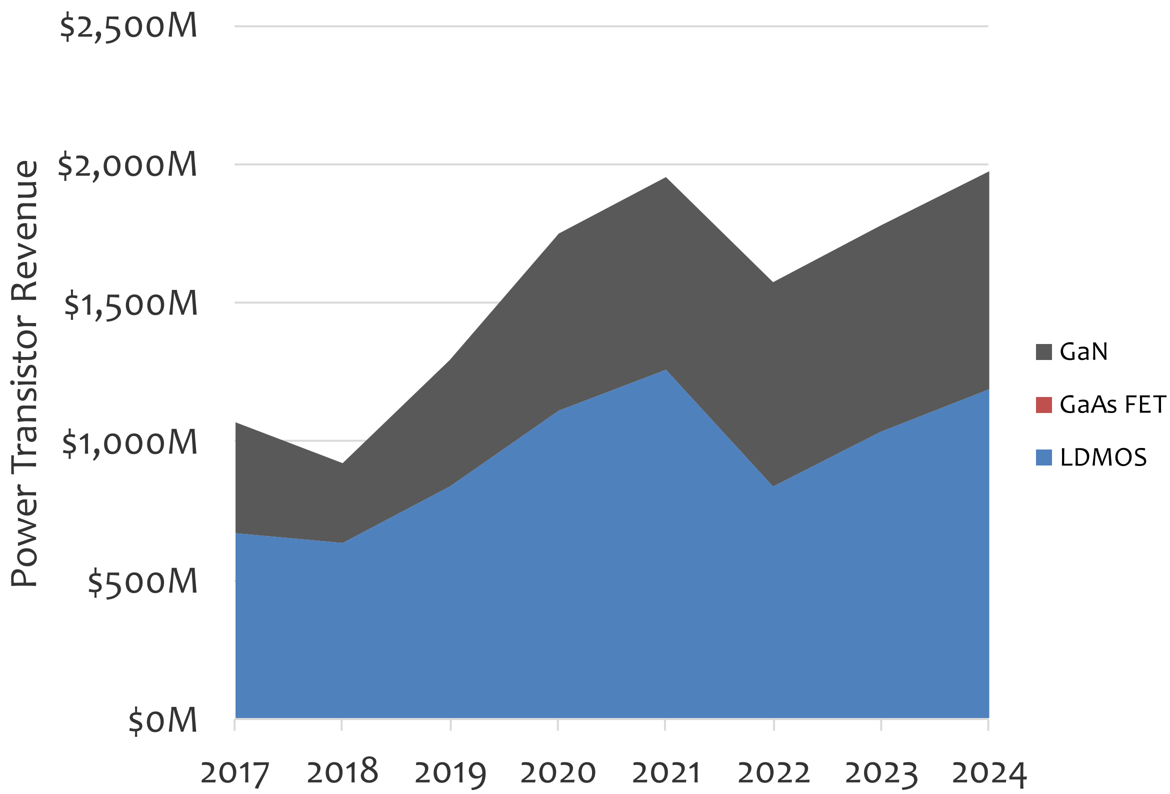

Chart 18: Power Transistor Market, by semiconductor process technology, 2017-2024

Source: Mobile Experts

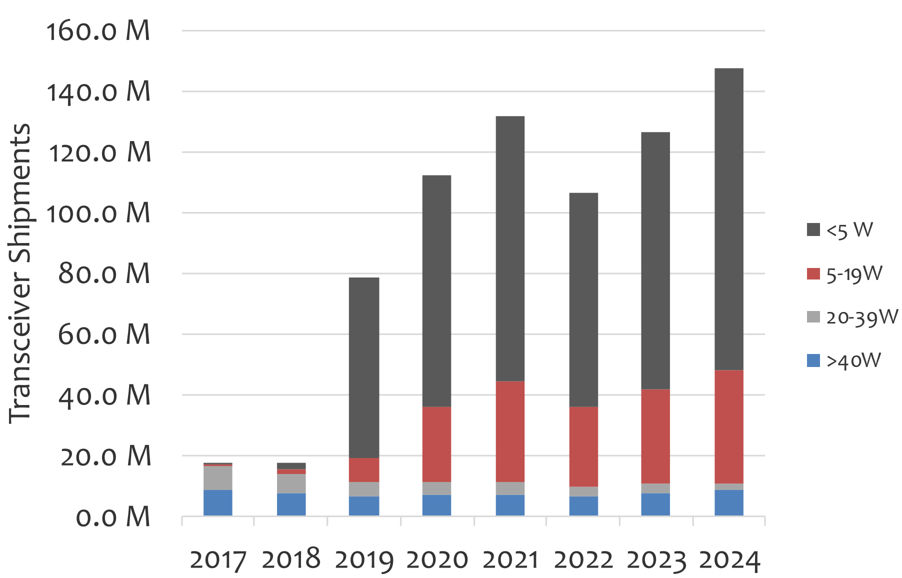

Chart 19: Transceiver shipments, by RF power level, 2017-2024

Source: Mobile Experts. Note: Including 20 million extra 'transceivers' in extra inventory, in the 5W category

One reason that the RF power forecast shifts to higher power in 2021 is that we expect a shift from heavy use of 64T64R radios to higher use of 16T and 8T radios in the 2021-2022 timeframe. When Chinese cities are covered and the deployment turns toward rural areas, we don't think that Massive MIMO will be a good idea. The size and weight of the antennas would be expensive and cumbersome, and there's not much benefit with low traffic levels. Note that Massive MIMO can help with better coverage due to higher antenna gain, but we think that cost issues will outweigh this benefit for most of China's rural base stations.

Note that the baseline configuration in China is moving from 240W (64 x 3.7W) to 320W (64 x 5W), so we have accounted for the boost in power with an uptick in pricing in the 2019-2020 timeframe. This upward migration of power level may also be an issue for LDMOS, as power efficiency and linearity become even more critical at higher power.

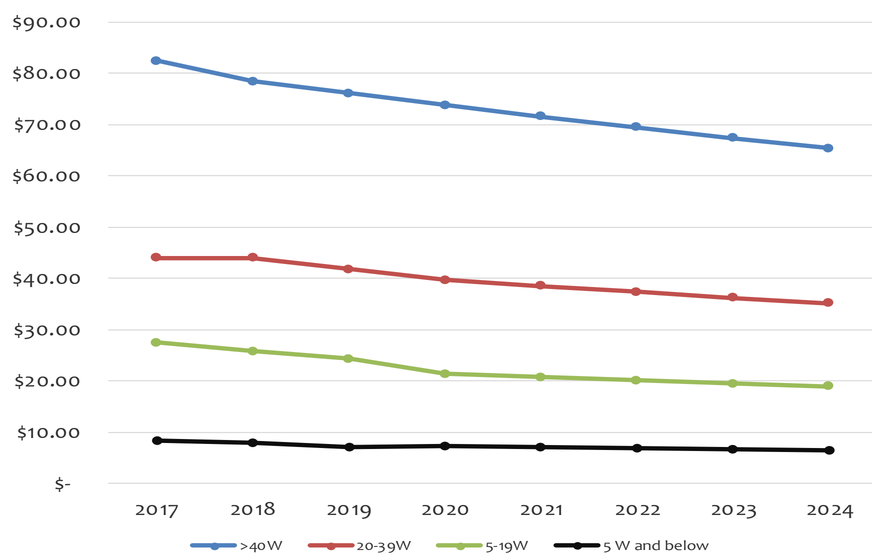

Chart 20: Power Transistor Dollar Content for various Transceiver Power Levels

Source: Mobile Experts

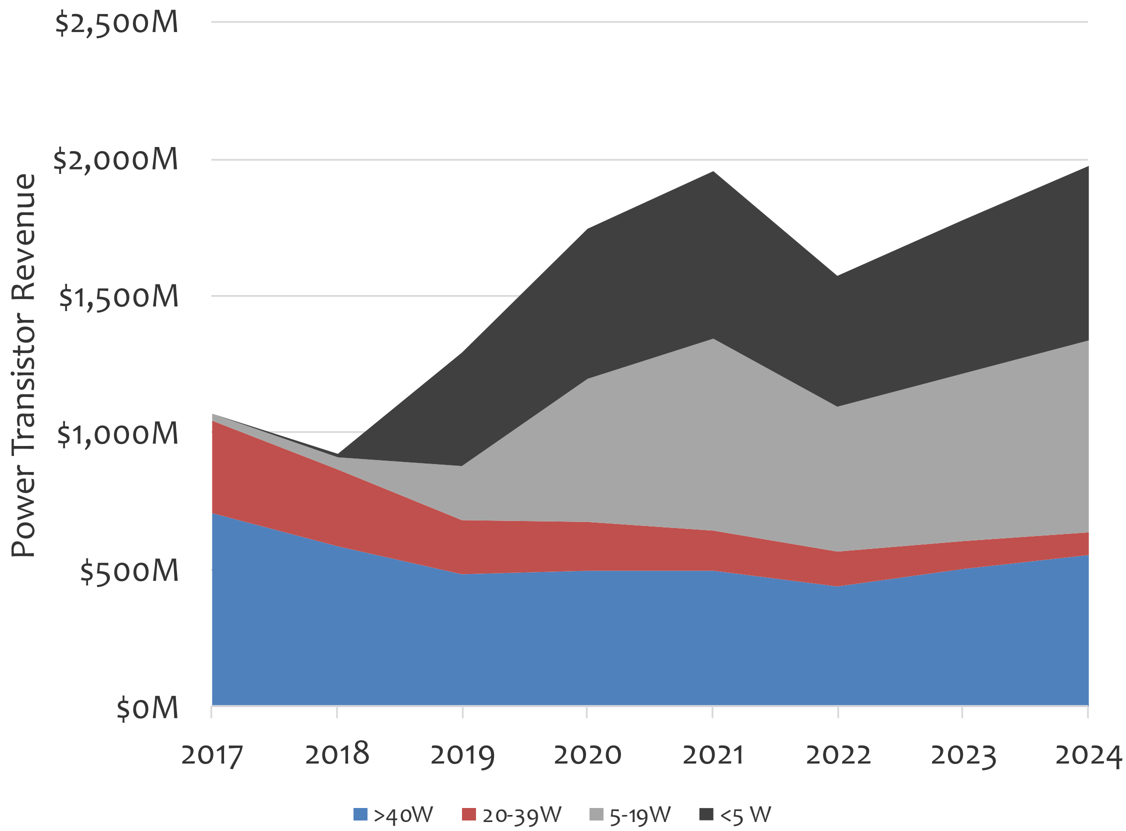

Chart 21: Power Transistor Revenue, by Radio Power Level

Source: Mobile Experts

In China, there will be a shift from 240W total power (64T) to 320W conducted power, which represents a 50% increase in power at the device level as well. Still, the emphasis lies on devices that we categorize as "driver amplifiers" due to the peak power in the range of 15W to 59W. The increase of peak power for China's expected shift won't affect things like packaging or linearization very much.

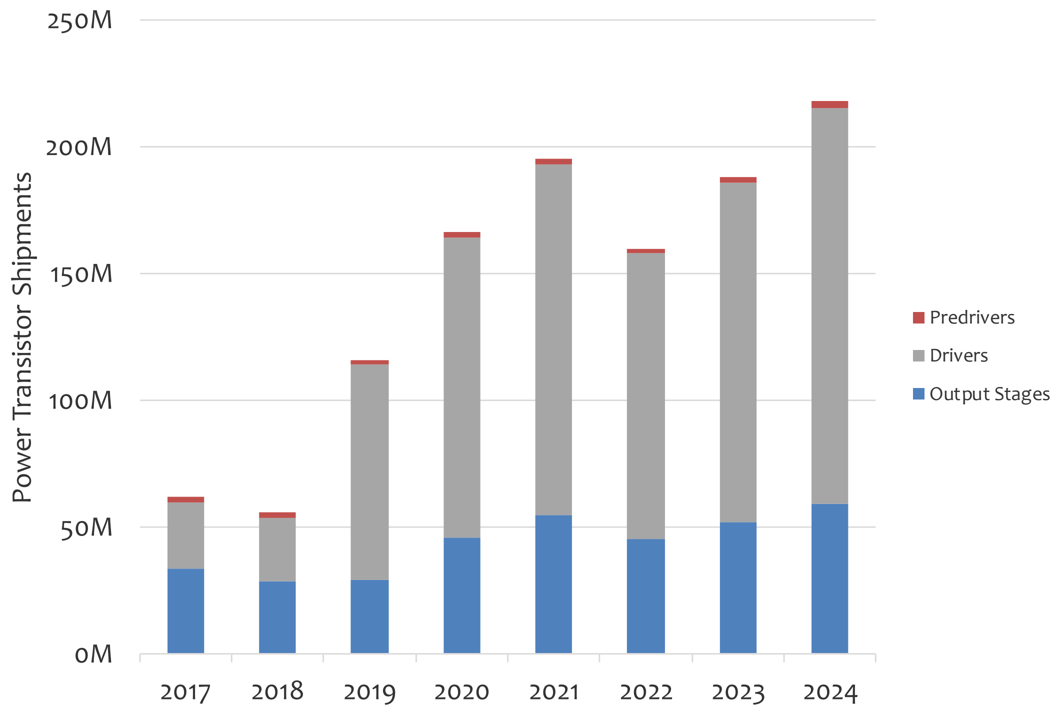

Chart 22: Power Transistor Shipments by Output/Driver/PreDriver stages

Source: Mobile Experts

PRIMARY PROCESSOR OUTLOOK

We've changed our segmentation of the processor market in the RRH, because our old categories of "ASIC", "FPGA" and "SoC" are no longer meaningful. Both FPGA and ASIC vendors use ARM cores in their RRH products, and "RFSoC" carries a new meaning in terms of including the data converter function. So, this year we chose to illustrate the market using four categories: FPGA and ASIC represent the extension of the traditional market, with either programmable logic or a hardened ASIC without data converters, and RFSoCs of each type that include ADC and DAC.

We define the Primary Processor as the unit which performs the RF processing for the main signal path. Other functions such as observation path monitoring, sniffer receiver monitoring, Serdes, jitter clean-up, and DPD adaptation can also be done in this main unit, but those are not necessary. In the 5G era, we expect that some of the PHY and MAC processing will move into the RRH as well, as the system architecture moves from CPRI toward a split-baseband approach. In general, the standardized functions of PHY and MAC will move quickly toward ASIC, while the RF portion (especially beamforming) will resist the trend due to ongoing uncertainties about optimization.

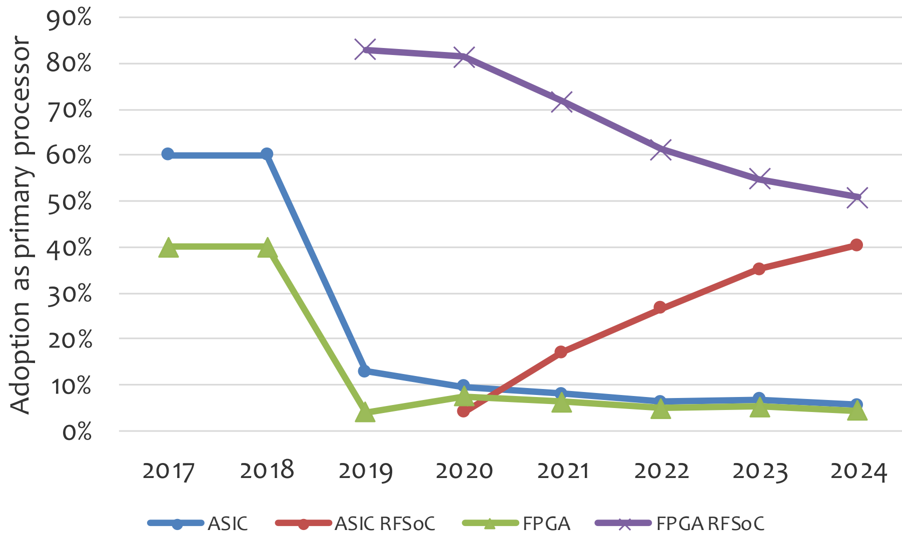

Chart 23: RRH Adoption of ASIC vs FPGA vs RFSoC, 2017-2024

Source: Mobile Experts

The adoption of ASIC/FPGA/RFSoC changes in our tracking sheet because the sudden growth of massive MIMO changes the percentage devoted to each architecture quickly.

As always, FPGA and ASIC prices will decline for the same functions over time. But in 5G there is more to be done, with wider bandwidth and beamforming, among other features. We're modeling that a basic FPGA or ASIC will hold a fairly steady ASP in the short term, but then will resume the normal price erosion curve.

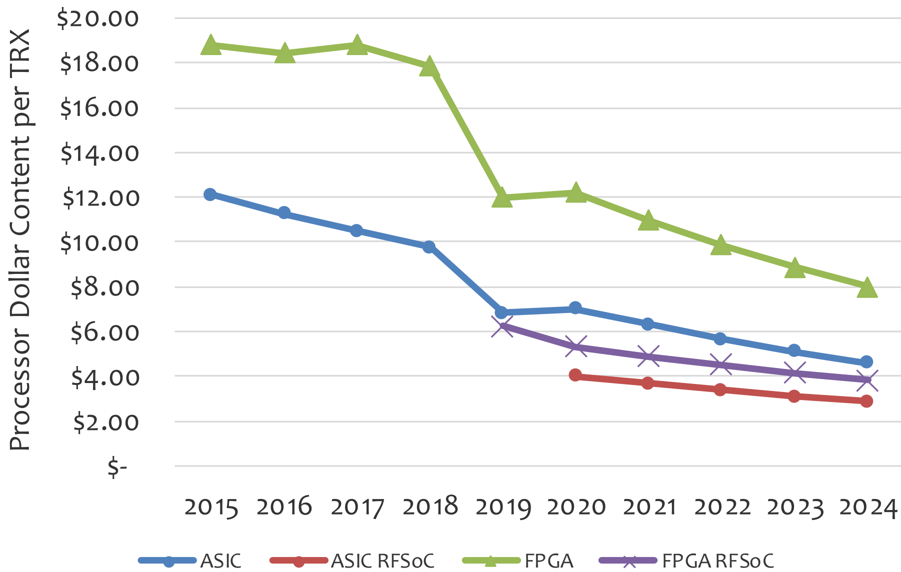

Chart 24: Dollar Content per RRH for ASIC, FPGA, and RFSoC, 2017-2024

Source: Mobile Experts

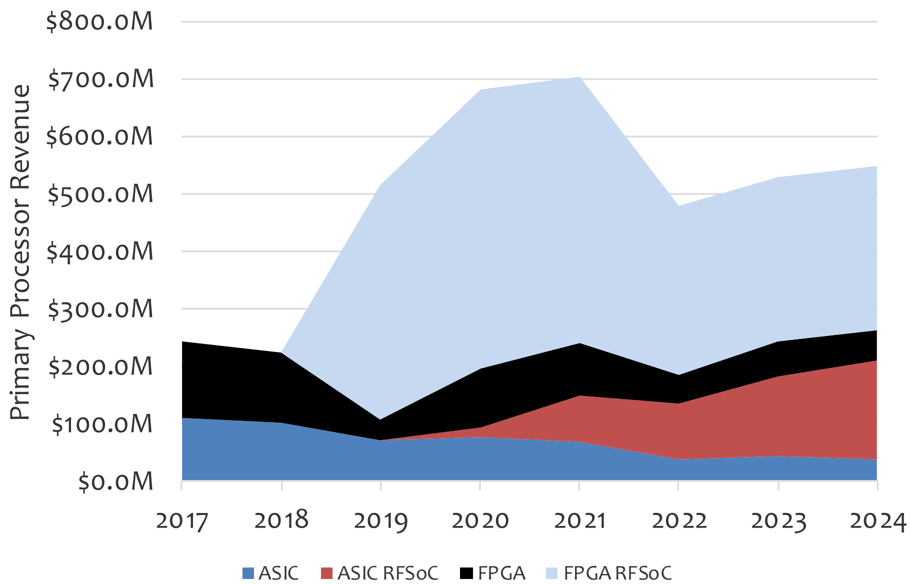

Chart 25: Primary Processor market for RRH, ASIC vs FPGA, 2017-2024

Source: Mobile Experts

Secondary Processor Outlook

The main path always has pressure to migrate toward low-cost ASICs, but some functions remain separate and are always best implemented on programmable logic. In particular, CPRI Serdes processing, radio "sniffing" receivers, alarms, calibration, and housekeeping functions such as temperature monitoring are best implemented on an FPGA. Almost all radio heads use a secondary FPGA for these purposes, keeping the chip as small and cheap as possible to support these functions.

Beamforming is one area that we expect to drive some content in secondary FPGAs, with sampling receivers and ancillary beamforming functions moving to the secondary unit when the primary processor is forced onto an ASIC.

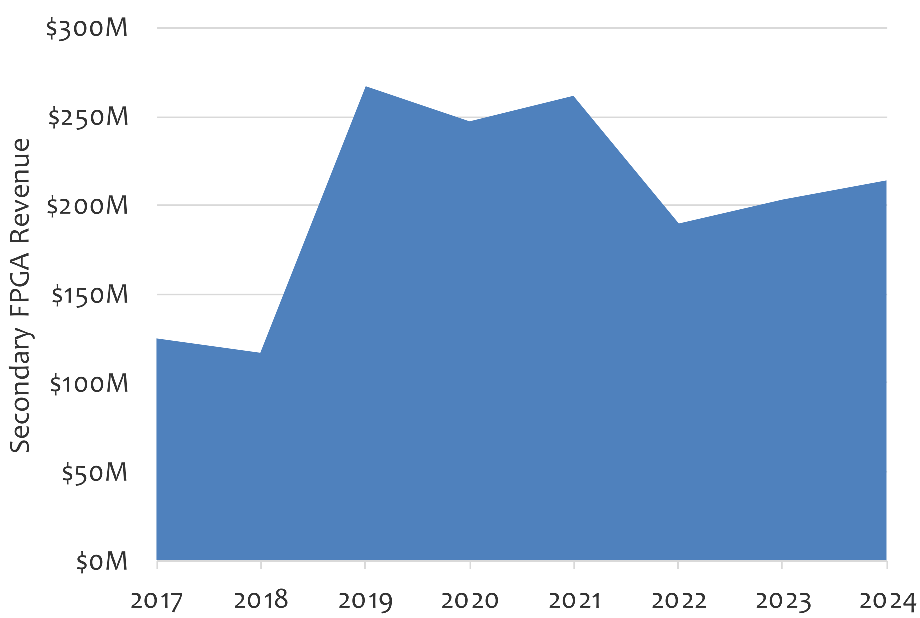

Chart 26: Secondary Processor Revenue for RRH, 2017-2024

Source: Mobile Experts

Data Converter (ADC/DAC) Outlook

Integration is coming to the data converters, and the traditional data converter suppliers have new competition as the digital world starts to gobble up their content. In the FDD world, ADI and TI have already started to integrate multi-channel modules so that two or four RF paths share a package. The next step, to be implemented mostly on TDD systems in Massive MIMO, will include integration of ADC and DAC into the processor.

The net impact of all this integration: The ADC and DAC vendors will benefit in the FDD world, and in TDD systems with low antenna count where a more discrete approach will pay off in terms of linearity/dynamic range performance. But they will lose content in the surging Massive MIMO market and miss out on the big growth wave. Over the next five years, we see the discrete data converter market as flat, with possible growth coming from integration of RF devices.

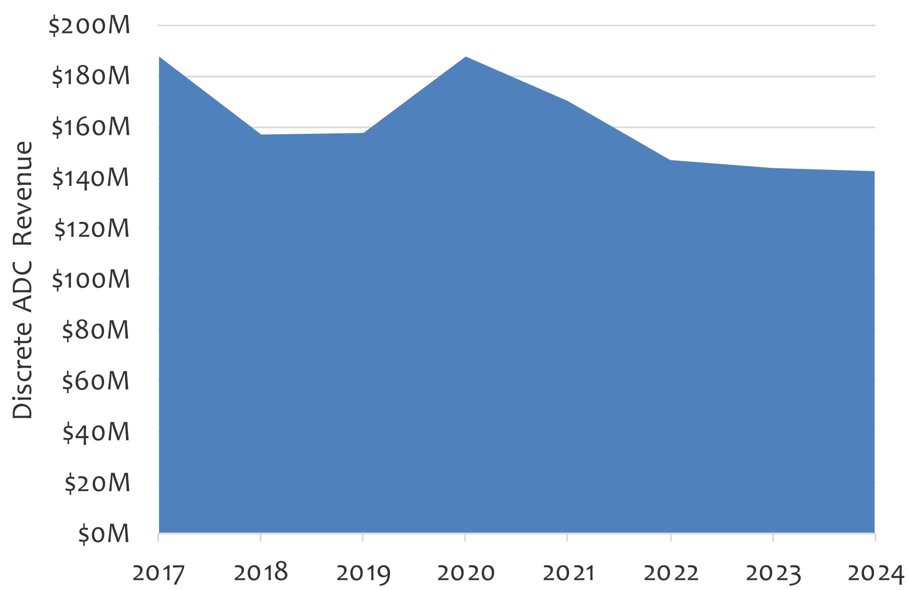

Chart 27: ADC Revenue in Macro RRH, 2017-2024

Source: Mobile Experts

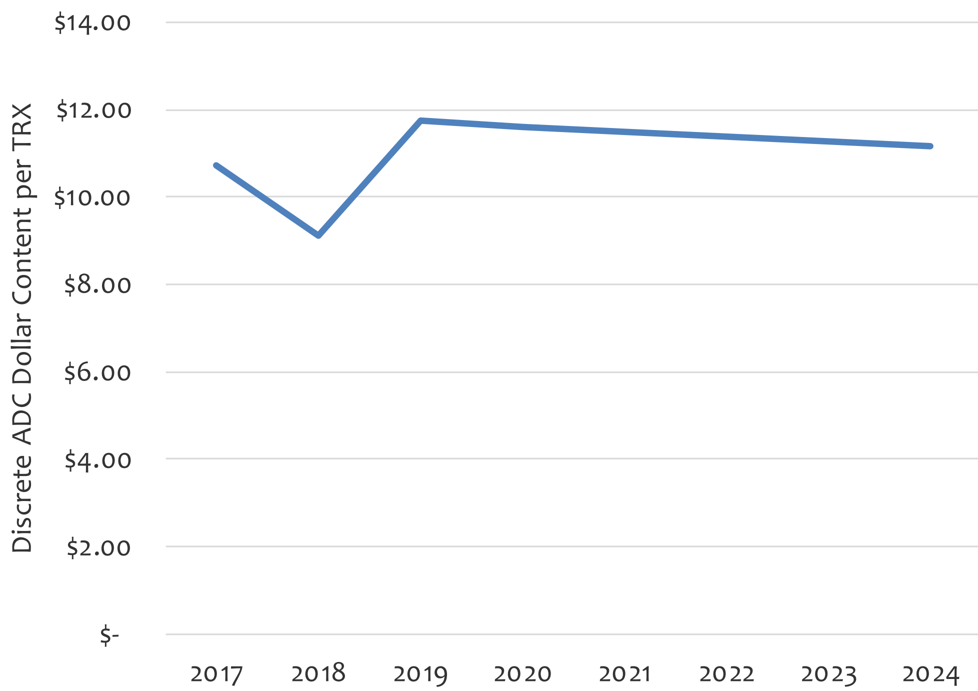

Chart 28: ADC Dollar Content per transceiver, 2017-2024

Source: Mobile Experts

Note: Dollar values apply only to non-massive MIMO radio units

DACs will follow a very similar trend. However, where ADCs are used in multiple 'extra' applications such as sampling paths, sniffing receivers, and other areas, DACs are generally only used for transmitters and therefore are used just in the main path. In many cases, the ADC and DAC will be integrated together so we expect fierce competition where ADI, TI, Maxlinear, and other vendors fight to keep their places in the lineup. The below charts illustrate the dollar value that we allocate to the DAC and its related RF integration, for non-massive MIMO radios only. (In Massive MIMO radios, the DAC has been integrated out of this category)

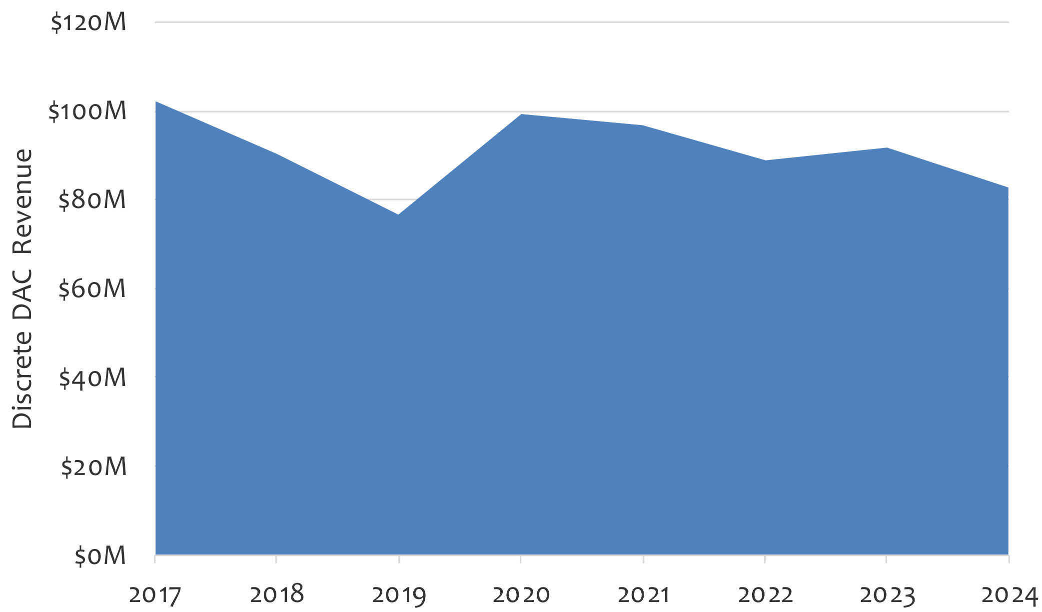

Chart 29: DAC Market Size in Macro Base Stations,, 2017-2024

Source: Mobile Experts

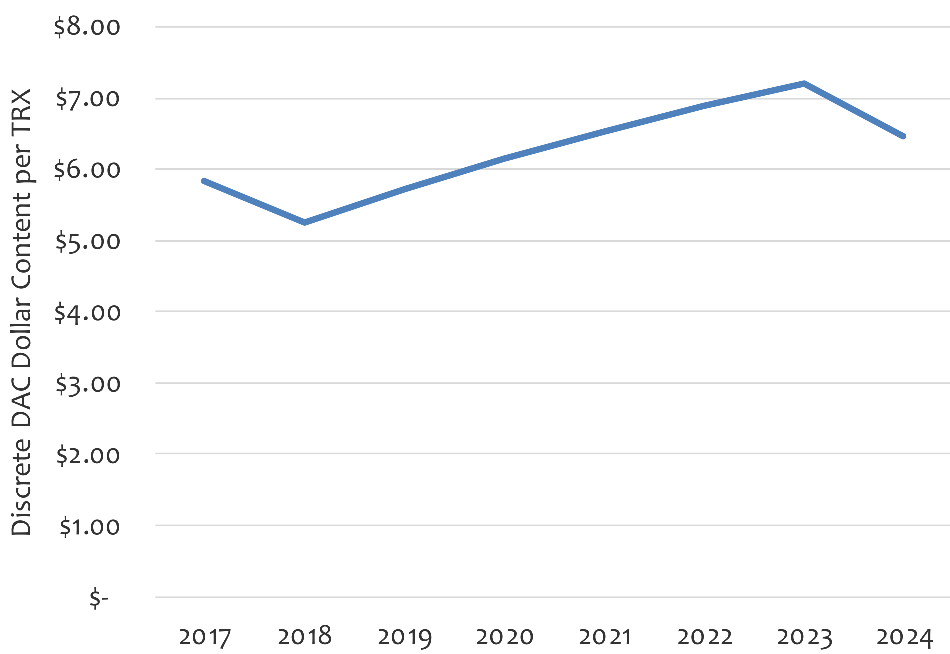

Chart 30: DAC Dollar Content per transceiver, 2017-2024

Source: Mobile Experts.

Note: Dollar figures include RF integration but only apply to non-massive MIMO radios.

PLL, VCO, AQM, and Small Signal RF Outlook

The RF components market will evaporate a bit, as many components will be integrated into the transceiver. On the other hand, massive MIMO is increasing the use of switches, filters, and LNAs in the front end.

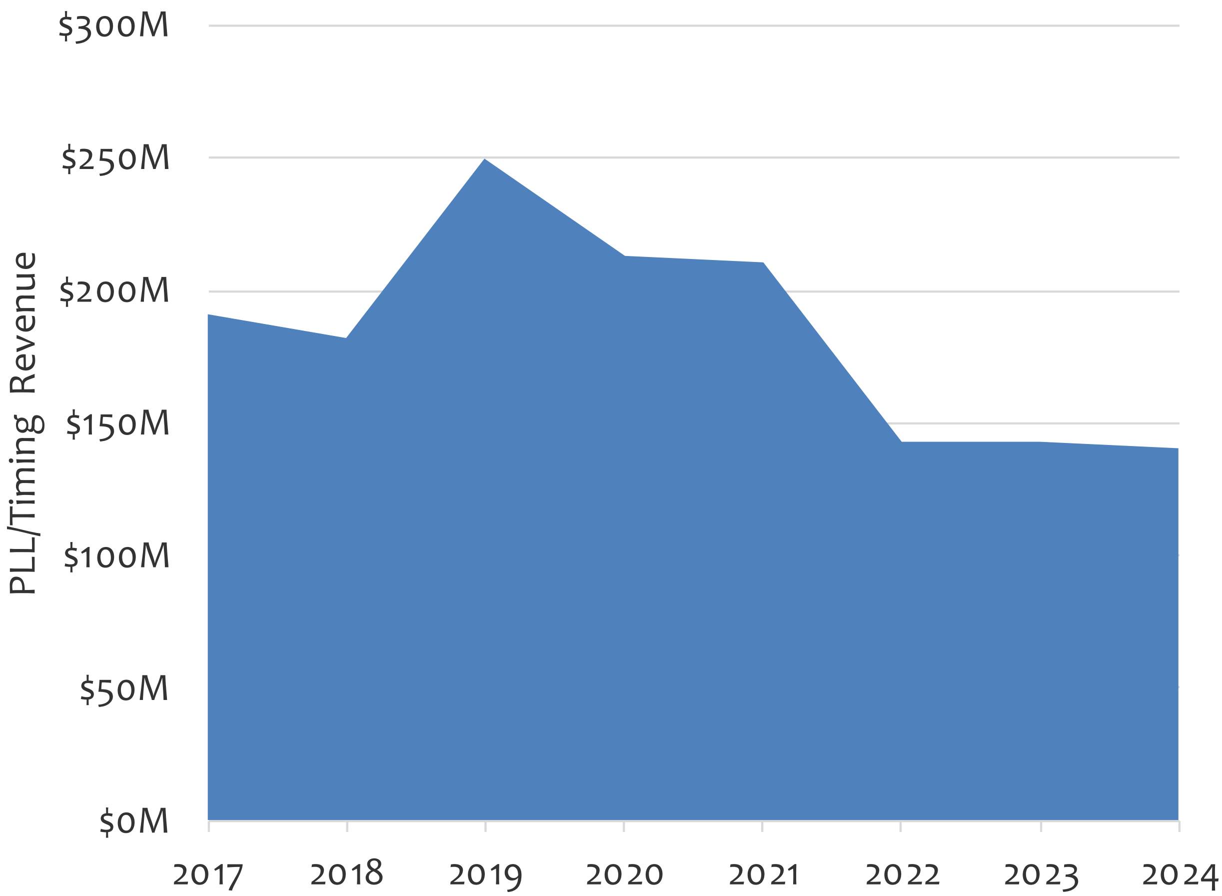

Chart 31: PLL/Timing Market Size in Macro base station RRH, 2017-2024

Source: Mobile Experts

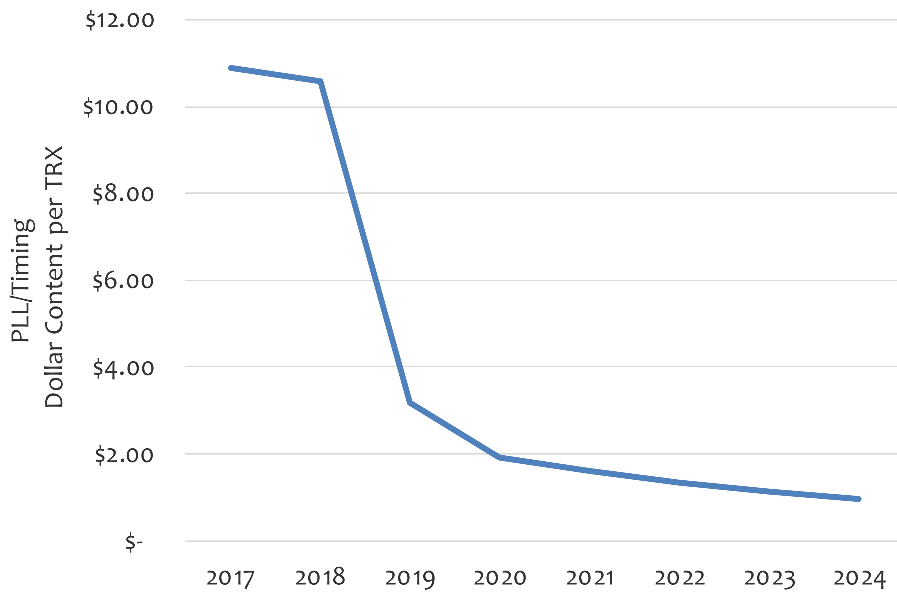

Chart 32: PLL/Timing Dollar Content per transceiver, 2017-2024

Source: Mobile Experts

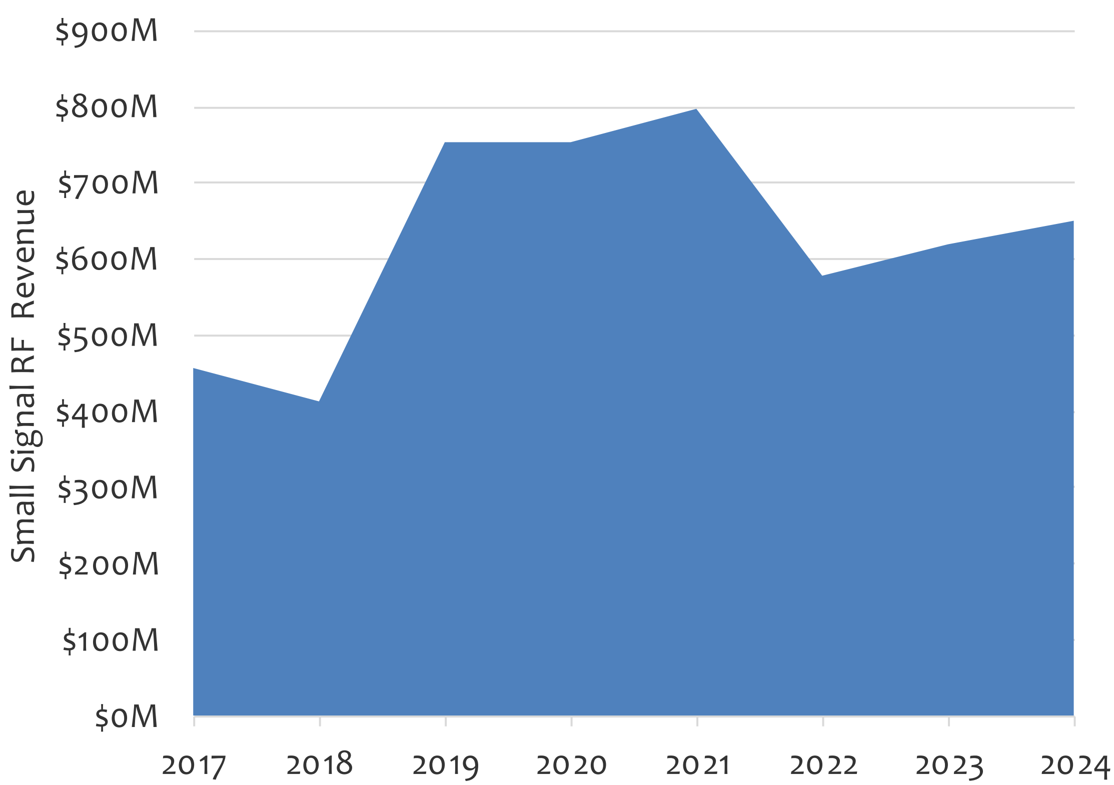

Chart 33: Small Signal RF Market Size in macro base stations, 2017-2024

Source: Mobile Experts

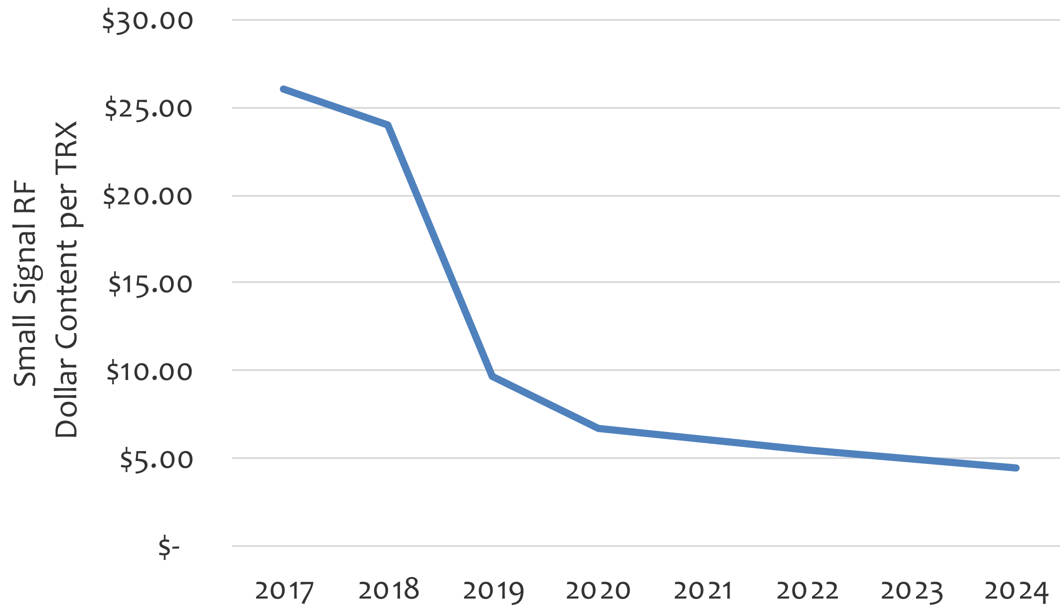

Chart 34: Small Signal RF Dollar Content per RRH, 2017-2024

Source: Mobile Experts

6 COMPANY PROFILES

AMPLEON:

Ampleon is the spinoff from NXP, devoted to power transistors. The spinoff involved a major investment from Jianguang Asset Management Co. (A Chinese state-owned investment company) for $1.8B. The company has a strong #2 position in the PA market, using LDMOS. They have GaN capability but so far have only used GaN in defense applications.

ANALOG DEVICES:

ADI is a market leader for mixed-signal devices such as analog-to-digital converters and digital-to-analog converters for mobile infrastructure. ADI's main differentiation comes from high performance (high dynamic range and wide bandwidth). With their RadioVerse product line, ADI integrates up/downconversion functions into the data converter device.

BROADCOM (AVAGO):

Broadcom supplies amplifiers, switches and other advanced devices for generic RF processing applications, and have a strong line of low noise, high dynamic range devices that can be used in the mobile transceiver chain. Broadcom supplies a large share of the LNAs in mobile infrastructure.

Broadcom/Avago also acquired LSI Logic in early 2014, consolidating two ASIC suppliers that offer support to the RRH market. Avago sold the Axxia (ASIC) product line to Intel in 2014. Also, Broadcom divested the Optichron/Netlogic product line to Nokia in early 2016. The net result is that Broadcom has the ability to support ASICs for advanced 5G base stations.

CREE/WOLFSPEED:

CREE is the parent company for Wolfspeed. CREE operates other businesses for SiC and GaN devices in lighting and other markets. See Wolfspeed.

E-ASIC (NOW INTEL)

eASIC Corporation was acquired by Intel in 2018. See Intel.

ERICSSON:

Ericsson is a major supplier of base station hardware, software, and services for operators. The company has strong radio design capability and leads in areas of Massive MIMO development in both sub-6 GHz and mm-wave areas. Ericsson typically designs their own ASICs, DPD algorithms, amplifiers, and radio boards. The company has lost some market share as Chinese competitors stole the developing market and the European market now represents a smaller share of the global total… but they are still strong in key leadership markets such as Korea, Japan, and the USA.

FUJITSU:

Fujitsu supplies specific components to mobile infrastructure applications, including some specialized DACs, driver amplifiers, and GaAs FET devices. As the Japanese vendors failed to export base stations worldwide during the past 20 years, Fujitsu has struggled to gain market share… but with the ban on ADC/DAC shipments from US companies to Huawei, Fujitsu has an opportunity to take a leading role.

HISILICON:

HiSilicon is a wholly owned subsidiary of Huawei, devoted to chipset development in base station and handset markets. The company has developed a process for iterating the design of an ASIC every three months, resulting in low development cost and a large variety of different ASIC options on each process node. ARM cores are used for some of the computing functions to maintain some flexibility. HiSilicon has not satisfied every need at Huawei, so opportunities remain for FPGAs and other ASIC suppliers. HiSilicon supports about two-thirds of Huawei's production requirements for primary processors in the RRH.

With the recent shutdown of FPGA-based RFSoC shipments, HiSilicon is engaged in a crash program to develop an ASIC-based alternative that handles the 5G radio functions as well as ADC and DAC integration. The viability of this product is unlikely in 2019 but may emerge in 2020.

HUAWEI TECHNOLOGIES:

Huawei Technologies has grown to #1 in the base station market, and is in prime position to take a leading share of the 5G ramp during 2019. Huawei has eased up on the super-aggressive pricing it offered worldwide, focusing more recently on profitability. Huawei designs its own ASICs through HiSilicon and also designs its own amplifiers and RF boards.

Huawei is currently in a crisis situation, as the US Dept of Commerce has banned American companies from supplying key semiconductors to Huawei. Without the RFSoC and ADC/DAC devices, Huawei may be forced to compromise performance in their 5G base stations.

INFINEON (SEE WOLFSPEED)

Infineon's LDMOS business was acquired by Cree in 2018, and was folded into the Wolfspeed business unit. See Wolfspeed.

INTEL:

Intel offers FPGAs as well as ASICs for the macro base station market. The company acquired the Axxia ASIC product line from LSI/Avago in 2014. Intel acquired Altera in December 2015, then added eASIC as of July 2018. This creates a pretty complete spectrum of solutions ranging from fully programmable R&D platforms (FPGAs) to ASICs with ARM cores and quick-turn ASICs. Despite all this activity, Intel is behind Xilinx in terms of data converter integration, which has become a critical feature.

LATTICE SEMICONDUCTOR:

Lattice Semiconductor supplies Serdes, housekeeping, and interface solutions using off-the-shelf FPGAs for the remote radio head market, and has focused its efforts on the "secondary" processor market, taking advantage of the holes in many RRH designs that need an inexpensive processor instead of a high-end FPGA.

MAXIM INTEGRATED PRODUCTS:

Maxim provides a broad range of discrete devices for the mobile infrastructure transceiver chain, including amplifiers, switches, buffer amplifiers, detectors, quadrature modulators, and other devices. The company acquired Scintera Networks in 2014 and merged the Scintera linearization products into the Maxim product line… hoping to take advantage of the Massive MIMO trend in low-cost predistortion. This was successful in small cells but may not be used as widely in massive MIMO systems.

MAXLINEAR:

Maxlinear acquired the RF product line of PMC-Sierra after the parent company was acquired by Microsemi. This group has developed integrated devices such as their SynthePHY, UniTX, and UniRX family of products which offer high dynamic range performance in an integrated module. In these modules, the mixed-signal devices are integrated with oscillators, modulators, and small signal RF devices to simplify the R&D process for the OEM. This integration approach competes against the vision of the Xilinx RFSoC, where the ADC/DAC are integrated with the processor instead.

MuRata:

Based in Japan, MuRata provides ceramic filters, SAW filters, and other passive devices for mobile infrastructure applications. MuRata also acquired Peregrine Semiconductor during 2014, adding digital step attenuators, phase shifters, and other small-signal RF devices to its offering. The company has the capability to integrate massive MIMO front ends with ceramic packaging in compact high-performance modules.

NanoSemi:

NanoSemi is a small company based in Boston with a new form of Digital Predistortion (DPD) which is more efficient than previous Volterra-based DPD solutions. The NanoSemi approach is especially effective over wide bandwidths, so it has strong potential for 5G applications. So far the company seems to be successful in convincing OEMs to license their DPD approach.

Nokia:

Nokia has built a leading base station company out of a wide collection of Nokia, Siemens, Alcatel, Lucent, Nortel, and Motorola product lines. The company has survived the integration issues of so many mergers, and now has emerged as the leading supplier of 5G base stations in terms of base station deals. Nokia has developed its own ReefShark chipsets for radio head and BBU applications, and in particular the company has inserted some innovative proprietary RF concepts. We can't disclose the details but our view is that Nokia is in position to achieve high efficiency in the RRH.

Nokia acquired Eta Devices (a provider of Envelope Tracking power supply devices and technology) in late 2016.

NXP Semiconductor:

NXP sells silicon power transistors which are fabricated using an LDMOS process, and has improved the fabrication process repeatedly over the years to result in low-cost devices with high linearity and efficiency. This group remains the #1 supplier in power transistor shipments and revenue.

NXP also has a line of GaN devices to stay competitive at high frequencies and high bandwidth. So far we believe that production has started but volume is relatively small.

QORVO:

Qorvo fabricates a wide variety of RF devices using Gallium Arsenide (GaAs) and Gallium Nitride (GaN) technology, including power amplifiers, switches, and low noise amplifiers for the mobile transceiver chain. With a wide product line in multiple process technologies, Qorvo holds significant share of the fragmented "multimarket RF" business.

Qorvo has finally broken into the power amplifier market, with GaN shipments to Huawei in early 2019. Note that these shipments were cut off by the US ban, leaving Qorvo with a big design win and a burst of volume followed by no shipments.

RFHIC:

RFHIC buys GaN die from CREE/Wolfspeed and sells the completed power transistors out of their operations in Korea. RFHIC has successfully established themselves as a more complete company, using the CREE fab but with their own design and applications engineering support based in Korea and China. Recently RFHIC has been working with GaN on diamond substrates for very high thermal performance. Their future, independent of the Cree fab, is uncertain.

SKYWORKS SOLUTIONS:

Skyworks has a strong product lineup for mobile infrastructure devices, with a long list of amplifiers, switches, mixers, VCOs/synthesizers, and quadrature modulators for the mobile transceiver chain. The company has tailored several of its devices for specific cellular bands to offer optimized performance.

TEXAS INSTRUMENTS:

Texas Instruments is a strong supplier of analog-to-digital converters and digital-to-analog converters, with good performance and some products tailored for the low cost market. The company also provides VCOs/PLLs for mobile infrastructure. Recently they've introduced products to integrate ADC/DAC/PLL/quad mod together for high performance, high efficiency, and small size. The company has strong relationships with all of the major OEMs.

WOLFSPEED:

Wolfspeed is a division of Cree, Inc. The company offers power transistors using Gallium Nitride material on Silicon Carbide wafers, as well as LDMOS devices from its acquisition of

Infineon's RF Power product line in 2018. Wolfspeed has strong relationships with multiple major OEMs and a solid position in the base station market.

XILINX:

Xilinx has led the market for FPGAs in RRH subsystems for many years, riding the changes from simple 3G RRH processing to DPD, beamforming, MIMO, and other innovations. The flexibility of their platforms is their primary differentiation over ASICs as the variation in RRH products cannot be anticipated by an ASIC design. As ASICs gain traction, Xilinx has responded by developing the RFSoC, combining ARM cores and FPGA processing as well as data converters for a very low power system solution. For 5G massive MIMO, we believe that ALL major OEMs have chosen to use the Xilinx RFSoC for early production.

ZTE:

ZTE is a major supplier of mobile infrastructure, and has some innovative techniques for TDD base stations and beamforming that could prove to be important in the 5G market. ZTE works with merchant ASIC suppliers to keep costs and power consumption down. This is an important company in the 5G era, because during the next five years Chinese operators are expected to dominate the market for 5G equipment and 80%+ of the production orders will go to Huawei, ZTE, Datang, and other Chinese companies.

The ban on US semiconductor shipments to Huawei may be good news for ZTE, as they now stand to capture a greater share of the Chinese 5G ramp.

7 ACRONYMS

2G: Second Generation Cellular
3G: Third Generation Cellular
4G: Fourth Generation Cellular
5G: Fifth Generation Cellular
2x2 MIMO: Two transmitters and two receivers for a single user
4x4 MIMO: Four transmitters and four receivers for a single user
4T4R: Four Transmitters and four receivers configured in the RRH
8T8R: Eight Transmitters and eight receivers configured in the RRH
64T64R: Sixty-four transmitters and sixty-four receivers configured in the RRH
AAS: Active Antenna System
ADC: Analog-to-Digital Converter
ASIC: Application Specific IC
ASP: Average Selling Price
ASSP: Application Specific Standard Product
AQM: Analog Quadrature Modulator
ARM: A processor with design licensed from ARM Holdings, Ltd.
ARPU: Average Revenue Per User
BAW: Bulk Acoustic Wave
BiCMOS: Bipolar Complementary Metal On Silicon
BTS: Base Transceiver Station
CA: Carrier Aggregation
CDMA: Code Domain Multiple Access, a 2G radio interface
CFR: Crest Factor Reduction
CoMP: Coordinated Multipoint
CPRI: Common Public Radio Interface, a non-profit organization and interface format
CRAN: Cloud Radio Access Network
DAC: Digital-to-Analog Converter
DAS: Distributed Antenna System
dB: Decibels (measuring relative difference in RF power levels)
dBc: Decibels with respect to the carrier power
DDC: Digital Downconverter
DFE: Digital Front End
DPD: Digital PreDistortion
DSP: Digital Signal Processing
DQM: Digital Quadrature Modulator
DUC: Digital Upconverter
eICIC: Enhanced Inter-cell Interference Coordination
ET: Envelope Tracking
EV-DO: CDMA Evolution-Data Optimized
EVM: Error Vector Magnitude
FDD: Frequency Division Duplex

FM: Frequency Modulated
FPGA: Field Programmable Gate Array
GaAs: Gallium Arsenide
GaN: Gallium Nitride
Gbps: Gigabits per second
GHz: Gigahertz
GSM: Global System for Mobile communications, a 2G radio interface
Gsps: Gigasamples per second
HBT: Heterojunction Bipolar Transistor
HSPA: High Speed Packet Access
Hz: Hertz
I/Q: In-phase/Quadrature modulation, a typical digital format for a communications signal
IAR: Integrated Antenna Radio
IC: Integrated Circuit
IF: Intermediate Frequency
IP: Intellectual Property
JESD204A/B: Serial interface standards, set by JEDEC (Joint Electron Device Engineering Council)
kHz: Kilohertz
LDMOS: Laterally Diffused Metal on Silicon
LNA: Low Noise Amplifier
LO: Local Oscillator
LTE: Long Term Evolution
Mbps: Megabits per second
MC-GSM: Multicarrier GSM
MHz: Megahertz
MIIT: Ministry of Industry and Information Technology (Chinese government agency)
MIMO: Multiple Input-Multiple Output
Msps: Megasamples per second
MU-MIMO: Multi-User MIMO
O&M: Operation & Maintenance
OBSAI: Open Base Station Architecture Initiative, a non-profit organization and interface format
OCXO: Ovenized Crystal Oscillator
OEM: Original Equipment Manufacturer
OFDM: Orthogonal Frequency Division Multiplexing
PA: Power Amplifier
PAD: Packaged Asymmetric Doherty
PAR: Peak-to-Average Ratio
PEP: Peak Envelope Power
PHY: Physical Layer
PIN: A diode type, using p-type, interface, and n-type semiconductor material
PLL: Phase Locked Loop
POE: Power Over Ethernet

QSFP: Quad Small Form Factor Pluggable
R&D: Research & Development
RAN: Radio Access Network
RF: Radio Frequency
RFSoC: Radio Frequency System on Chip
RMS: Root-Mean Squared
RRH: Remote Radio Head
Rx: Receiver
SAW: Surface Acoustic Wave
SFP: Small Form Factor Pluggable
SiGe: Silicon Germanium
SNR: Signal-to-Noise Ratio
SoC: System-On-Chip
TCXO: Temperature Compensated Crystal Oscillator
TDD: Time Division Duplex
TD-SCDMA: Time Division Synchronous Code Domain Multiple Access
TD-LTE: Time Division Duplexed LTE (A 4G standard)
Tx: Transmitter
VCO: Voltage Controlled Oscillator
VCTCXO: Voltage Controlled Temperature Compensated Crystal Oscillator
W: Watts of power
W-CDMA: Wideband Code Domain Multiple Access, a 3G radio interface

8 METHODOLOGY

To create estimates and forecasts for base station equipment shipments, Mobile Experts relies on direct input from more than 40 industry sources, including multiple top OEM vendors, mobile operators, and component suppliers.

Mobile Experts also used financial disclosures from publicly traded companies to assemble a quantitative view of the equipment market, and to establish estimates of the expected trends in the near future.

In particular, Mobile Experts uses a "top down and bottom up" approach to the base station transceiver forecast, in which inputs from the operators and OEMs are balanced against shipment data provided by key component suppliers. Several component suppliers participate in the Mobile Experts Data Sharing Program, in which they provide quarterly or annual shipment data on key components, which can help Mobile Experts to track shipments by frequency band.

The semiconductor content in the transceivers was assessed by interviewing multiple companies in each semiconductor segment, gathering information on application of the devices, performance trends, market shares, and costs. Each semiconductor type was assessed for the cost in single-mode and multi-mode radios, in each air interface standard, in order to determine the total market size for each semiconductor type across the total number of transceivers. Data for different components are compared to improve accuracy (i.e. the power transistors, processors, and data converters should all be aligned to the same total shipment numbers).

Transceivers are broken out by the physical configuration (2T2R, 4T4R, 64T64R) as well as by power level and by frequency band. A massive MIMO RRH with two 64T64R panels is counted as a single 128T128R in our forecast. Note that Mobile Experts uses ***transceivers*** as our primary tracking metric, not base stations, in order to have the most accurate forecast possible for RF devices.

This year, Mobile Experts adjusted for the buildup of inventory by Huawei by adding 20 million transceiver shipments to our system-level forecast. The impact of this decision is that our *Semiconductors for RRH* forecast includes more devices than our system level shipment forecast. Our intention is to accurately reflect the decision by Huawei to hold a large number of FPGA RFSoCs, power transistors, and other American components in inventory.

In addition, multimode transceivers are listed according to the air interface standard used during initial deployment. (An HSPA/LTE capable transceiver that is shipped initially for 3G will be listed in the 3G category despite any plans for software upgrades to LTE in the future)

Processors are divided into “primary” and “secondary” categories according to the placement of the main-path RF processing.   PHY processing and any main-path RF processing defines the “primary” processor in a split-baseband RRH.

Power transistors are listed as “output stages” if the peak envelope power exceeds 60w. Driver stages have peak envelope power between 15W and 59 W, and pre-driver stages are below 15 PEP.